

# **COST CA 19111**

## **European Network on Future Generation Optical Wireless Communication Technologies (NEWFOCUS)**

### **Milestone M3.1**

#### **VLC and FSO Channel modelling & PHY and MAC design**

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## Introduction

Based on the overall goal of NEWFOCUS WG3, which is to develop practical high-reliability VLC-based solutions for smart-cities, such as vehicular and underwater and high bitrate point-to-point FSO links for deployment in backhaul/fronthaul infrastructures, Milestone 3.1 has been successfully accomplished, as demonstrated in the internal documents discussed in the Project meetings and, also, evidenced in the publications detailed below.

In the following, the results are presented according to the following structure:

1. Vehicular communications
2. Optical Camera Communications
3. Underwater communications
4. Outdoor FSO/VLC links
5. Microwave Photonics links for Radio-over-Fiber and FSO communications

### 1. Vehicular communications

Concerning VLC-based vehicular networks, channel models have been developed taking into account road infrastructure and fast moving vehicles. The effects of weather and environmental conditions, ambient noise, and link misalignments have been investigated in detail.

Internal documents:

- Northumbria University (UK), Czech Technical University in Prague (CZ):  
“Performance of Vehicular Visible Light Communications under the Effects of Atmospheric Turbulence with Aperture Averaging” (2nd meeting)
- Northumbria University (UK), Universidad de Las Palmas (ES):  
“Optical Camera-based Road-to-Vehicle Communication” (2nd meeting)

Publications:

- (UK/CZ) E. Eso, Z. Ghassemlooy, S. Zvanovec, J. Sathian, M. M. Abadi, and O. I. Younus, “Performance of Vehicular Visible Light Communications under the Effects of Atmospheric Turbulence with Aperture Averaging,” *Sensors*, vol. 21, no. 8, p. 2751, Apr. 2021, doi: [10.3390/s21082751](https://doi.org/10.3390/s21082751).
- (ES/CZ)V. Matus, V. Guerra, C. Jurado-Verdu, S. Zvanovec, and R. Perez-Jimenez, “Wireless sensor networks using sub-pixel optical camera communications: Advances in experimental channel evaluation,” *Sensors*, vol. 21, no. 8, 2021, doi: [10.3390/s21082739](https://doi.org/10.3390/s21082739).
- (UK/CZ/IR) E. Eso, Z. Ghassemlooy, S. Zvanovec, J. Sathian and A. Gholami, "Fundamental Analysis of Vehicular Light Communications and the Mitigation of Sunlight Noise," in *IEEE Transactions on Vehicular Technology*, vol. 70, no. 6, pp. 5932-5943, June 2021, doi: [10.1109/TVT.2021.3078576](https://doi.org/10.1109/TVT.2021.3078576).
- (TR/UK/DE/CZ) H. B. Eldeeb, E. Eso, E. A. Jarchlo, S. Zvanovec, M. Uysal, Z. Ghassemlooy, J. Sathian, "Vehicular VLC: A Ray Tracing Study Based on Measured Radiation Patterns of Commercial Taillights," in *IEEE Photonics Technology Letters*, vol. 33, no. 16, pp. 904-907, 2021, doi: [10.1109/LPT.2021.3065233](https://doi.org/10.1109/LPT.2021.3065233).

- (UK/CZ) E. Eso, Z. Ghassemlooy, S. Zvanovec, P. Pesek, J. Sathian, "Vehicle-to-Vehicle Relay-Assisted VLC With Misalignment Induced Azimuth or Elevation Offset Angles," in IEEE Photonics Technology Letters, vol. 33, no. 16, pp. 908-911, 2021, doi: [10.1109/LPT.2021.3086836](https://doi.org/10.1109/LPT.2021.3086836).
- (FR/IT) M. Mayahi, A. Costanzo, V. Loscrí and A. M. Vegni, "An Interference to Noise Ratio Handover mechanism for Mobile Visible Light Communication Networks," 2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), Porto, Portugal, 2022, pp. 457-462, doi: [10.1109/CSNDSP54353.2022.9907915](https://doi.org/10.1109/CSNDSP54353.2022.9907915).

## 2. Optical Camera Communications

Channel evaluation and camera data processing techniques for outdoor applications like sensor networks has been also performed with regards to Optical Camera communications within NEWFOCUS framework.

Internal documents:

- Universidad de Las Palmas (ES), Czech Technical University in Prague (CZ):  
"Wireless sensor networks using sub-pixel camera communication" (2nd meeting)
- IDeTIC Universidad de Las Palmas (ES), Czech Technical University in Prague (CZ):  
V. Matus, V. Guerra, C. Jurado-Verdu, S. Zvanovec, R. Perez-Jimenez, "Wireless Sensor Networks Using Sub-Pixel Optical Camera Communications: Advances in Channel Evaluation" (3rd meeting)
- IDeTIC Universidad de Las Palmas (ES), Czech Technical University in Prague (CZ):  
C. Jurado-Verdu, V. Guerra, C. Guerra-Yáñez, J. Rabadán, S. Zvanovec, R. Perez-Jimenez, "Deep learning in Optical Camera Communication : Advances in exposure-related ISI equalization" (5th meeting)

Publications:

- (ES/CZ) V. Matus, V. Guerra, C. Jurado-Verdu, S. Zvanovec, and R. Perez-Jimenez, "Wireless sensor networks using sub-pixel optical camera communications: Advances in experimental channel evaluation," Sensors, vol. 21, no. 8, 2021, doi: [10.3390/s21082739](https://doi.org/10.3390/s21082739).
- (ES/CH) C. Jurado-Verdu, V. Guerra, J. Rabadan, and R. Perez-Jimenez, "Deep learning for signal clock and exposure estimation in rolling shutter optical camera communication," Opt. Express, vol. 30, no. 12, p. 20261, Jun. 2022, doi: [10.1364/OE.458538](https://doi.org/10.1364/OE.458538).
- (ES/CZ) A. Mederos-Barrera, C. Guerra-Yanez, C. Jurado-Verdu, V. Guerra, J. Rabadan, R. Perez-Jimenez, S. Zvanovec, "Fractal Modulation Scheme for Optical Camera Communication," 2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), Porto, Portugal, 2022, pp. 140-144, doi: [10.1109/CSNDSP54353.2022.9908052](https://doi.org/10.1109/CSNDSP54353.2022.9908052).
- (ES/CH) C. Jurado-Verdu, V. Guerra, C. Guerra, J. Rabadan, S. Zvánovec and R. Perez-Jimenez, "On-demand training of deep learning equalizers for rolling shutter optical camera communications," 2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), Porto, Portugal, 2022, pp. 1-5, doi: [10.1109/CSNDSP54353.2022.9907920](https://doi.org/10.1109/CSNDSP54353.2022.9907920).

### 3. Underwater communications

For underwater VLC links, characterization and modelling of the aquatic channel have been studied under special conditions such as vertical links and turbulences, as well as considering localization applications.

Input documents:

- Institut Fresnel (FR), McMaster University (CA):  
"Parameter Optimization for an Underwater Optical Wireless Vertical Link Subject to Link Misalignments" (2nd meeting)
- "University of Poitiers (FR), Roma Tre University (IT), INRIA (FR):  
Performance Evaluation of Underwater Visible Light Positioning Algorithms using Realistic Propagation Model" (6th meeting)
- Northumbria University (UK), Czech Technical University in Prague (CZ):  
The effect of inter pixel interference on the performance of a multi-channel underwater optical camera communication (7<sup>th</sup> meeting)

Publications:

- (FR/CA) C. Ijeh, M. A. Khalighi and S. Hranilovic, "Parameter Optimization for an Underwater Optical Wireless Vertical Link Subject to Link Misalignments," in IEEE Journal of Oceanic Engineering, vol. 46, no. 4, pp. 1424-1437, Oct. 2021, doi: [10.1109/JOE.2021.3069046](https://doi.org/10.1109/JOE.2021.3069046).
- (DE/IT/FR) A.M. Vegni, M. Hammouda, and V. Loscrí, "A VLC-based Footprinting Localization Algorithm for Internet of Underwater Things in 6G networks," in Proc. Of 5th International Workshop on Optical Wireless Communications (IWOW) in conjunction with the 7th International Symposium on Wireless Communications, on 6-9 Sept. 2021, Berlin, Germany.
- (DE/IT/FR) M. Hammouda, A. M. Vegni, and V. Loscrí, "On the Noise Effect of Fingerprinting-Based Positioning Error in Underwater Visible Light Networks," Sensors, vol. 21, no. 16, p. 5398, Aug. 2021, doi: [10.3390/s21165398](https://doi.org/10.3390/s21165398)
- (FR/TR/CA) I. C. Ijeh, M. A. Khalighi, M. Elamassie, S. Hranilovic and M. Uysal, "Outage probability analysis of a vertical underwater wireless optical link subject to oceanic turbulence and pointing errors," in Journal of Optical Communications and Networking, vol. 14, no. 6, pp. 439-453, June 2022, doi: [10.1364/JOCN.454191](https://doi.org/10.1364/JOCN.454191).
- (IT/FR) A. M. Vegni and V. Loscrí, "Adaptive Visible Light Positioning with MSE Inner Loop for Underwater Environment," 2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), Porto, Portugal, 2022, pp. 601-606, doi: [10.1109/CSNDSP54353.2022.9907991](https://doi.org/10.1109/CSNDSP54353.2022.9907991).

### 4. Outdoor FSO/VLC links/networks

Efficient PHY techniques have been considered, including multiple-input multiple-output (MIMO), wavelength division multiplexing (WDM), multi-hop techniques and high spectrally efficient modulations, for the sake of increasing the link data rate and range. Moreover, cognitive features and optimized networking by software defined techniques have been addressed to overcome atmospheric conditions and also allow hard/soft switching between different link types enabling resource management architectures. Experimental and theoretical performance analyses have been employed for characterizing and modelling the optical channels of different implementations.

#### Input documents:

- Northumbria University (UK), Czech Technical University in Prague (CZ):  
An Experimental Testbed for Implementation and Validation of Software Defined FSO Under Atmospheric Conditions using USRPs (4th meeting)
- Northumbria University (UK), Institut Fresnel (FR):  
Software-Defined Networking for Free Space Optical Communication (4th meeting)
- Northumbria University (UK), Institut Fresnel (FR):  
Demonstration of An Optical Wireless Communication System using a Software-Defined Ecosystem (5th meeting)
- Slovak University of Technology (SK), Brno University of Technology (CZ)  
The Performance Analysis of the FSO System Utilization in the Long Reach PON Network using the HPON Network Configurator (7th meeting)
- Brno University of Technology (CZ), Slovak University of Technology (SK)  
Optical Ray Transfer Matrix Model of the Turbulent Cells Cascade (7th meeting)

#### Publications:

- (UK/CZ) Z. Htay, Z. Ghassemlooy, M. M. Abadi, A. Burton, N. Mohan and S. Zvanovec, "Performance Analysis and Software-Defined Implementation of Real-Time MIMO FSO With Adaptive Switching in GNU Radio Platform," in IEEE Access, vol. 9, pp. 92168-92177, 2021, doi: [10.1109/ACCESS.2021.3092968](https://doi.org/10.1109/ACCESS.2021.3092968).
- (UK/CZ) N. Mohan, Z. Ghassemlooy, E. Li, M. M. Abadi, S. Zvanovec, R. Hudson, Z. Htay, "The BER performance of a FSO system with polar codes under weak turbulence," IET Optoelectron., vol. 16, no. 2, pp. 72–80, Apr. 2022, doi: [10.1049/ote2.12058](https://doi.org/10.1049/ote2.12058).
- (SK/ES) R. Róka, C. Stefanovic, M. Morales-Céspedes and A. G. Armada, "Performance Analysis of the FBMC Modulation Format in Optical Fiber and Wireless Communications," 2021 17th International Symposium on Wireless Communication Systems (ISWCS), Berlin, Germany, 2021, pp. 1-6, doi: [10.1109/ISWCS49558.2021.9562137](https://doi.org/10.1109/ISWCS49558.2021.9562137).
- (UK/CZ) A. Burton, P. Chvojka, P. A. Haigh, Z. Ghassemlooy, and S. Zvanovec, "Optical Filter-Less WDM for Visible Light Communications Using Defocused MIMO," Electronics, vol. 10, no. 9, p. 1065, Apr. 2021, doi: [10.3390/electronics10091065](https://doi.org/10.3390/electronics10091065).
- (SK/ES) C. Stefanovic, M. Morales-Céspedes, R. Róka and A. G. Armada, "Performance Analysis of N-Fisher-Snedecor F Fading and Its Application to N-Hop FSO Communications," 2021 17th International Symposium on Wireless Communication Systems (ISWCS), Berlin, Germany, 2021, pp. 1-6, doi: [10.1109/ISWCS49558.2021.9562174](https://doi.org/10.1109/ISWCS49558.2021.9562174).
- (SK/ES) R. Róka, C. Stefanovic, M. Morales-Céspedes and A. G. Armada, "Performance Analysis of the FBMC Modulation Format in Optical Fiber and Wireless Communications," 2021 17th International Symposium on Wireless Communication Systems (ISWCS), Berlin, Germany, 2021, pp. 1-6, doi: [10.1109/ISWCS49558.2021.9562137](https://doi.org/10.1109/ISWCS49558.2021.9562137).
- (SR/PL) M. Petkovic, G. Djordjevic, J. Makal, Z. Marjanovic, G. V. Milovanovic, "Error probability of a coherent M-ary PSK FSO system influenced by phase noise", Mathematics, vol. 11, no. 1, Paper 121, January 2023, doi: [10.3390/math11010121](https://doi.org/10.3390/math11010121)
- (GR/UK/CZ/PT/FR) T. Kamalakis, Z. Ghassemlooy, S. Zvanovec, L. Nero Alves, A. Khalighi, Optimization and Design of a Diffuse Optical Wireless Sensor Network, Applied Optics, vol. 61, no. 22, pp. 6599-6608, 2022, doi: [10.1364/AO.463330](https://doi.org/10.1364/AO.463330)

- (SR/PL) M. Petkovic, G. Djordjevic, J. Makal, Z. Marjanovic, G. V. Milovanovic, "Error probability of a coherent M-ary PSK FSO system influenced by phase noise", Mathematics, vol. 11, no. 1, Paper 121, 2023, doi: [10.3390/math11010121](https://doi.org/10.3390/math11010121)
- (GR/UK/CZ) T. Kamalakis, Z. Ghassemlooy, S. Zvanovec, L. Nero Alves, A. Khalighi, "Optimization and Design of a Diffuse Optical Wireless Sensor Network", Applied Optics, vol. 61, no. 22, pp. 6599-6608, 2022, doi: [10.1364/AO.463330](https://doi.org/10.1364/AO.463330)
- (UK/CZ) N. Mohan, Z. Ghassemlooy, E. Li, M.M. Abadi, S. Zvanovec, R. Hudson, Z. Htay, "The BER Performance of a FSO System with Polar Codes Under Weak Turbulence", IET Optoelectronics, vol. 16, pp. 72-80, 2022, doi: [10.1049/ote2.12058](https://doi.org/10.1049/ote2.12058)
- (CZ/SK) A. Kovalova, L. Hudcova, R. Roka, "Optical Ray Transfer Matrix Model of the Turbulent Cells Cascade", Radioengineering, vol. 31, no. 4, pp. 520-526, 2022, [10.13164/re.2022.0520](https://doi.org/10.13164/re.2022.0520)
- (SK/CZ) R. Roka, L. Hudcova, A. Kovalova, "The Performance Analysis of the FSO System Utilization in the Long Reach PON Network using the HPON Network Configurator", 45th Int. Conference on Telecommunications and Signal Processing, Prague (Czech Republic), TSP 2022 13-15, 7, 2022, doi: [10.1109/TSP55681.2022.9851251](https://doi.org/10.1109/TSP55681.2022.9851251)

## 5. Microwave Photonics links for Radio-over-Fiber and FSO communications

Microwave photonics has been proved as a powerful combined discipline to be exploited also in wireless communications where optical domain is employed for generation and processing radio signals. As it is well known, Radio over fiber/FSO links is an enabling technology for current and future networks deployment. NEWFOCUS consortium presented a large number of contributions where hybrid optical channels have been studied and evaluated for the sake of optimising the design of 5G and B5G networks.

Input documents:

- Czech Technical University in Prague (CZ), Universitat Politecnica de Valencia (ES), Northumbria University of Newcastle (UK):  
Radio over free space optics (RoFSO) for 5G (2<sup>nd</sup> meeting)
- Universitat Politecnica de Valencia (ES) , Czech Technical University in Prague (CZ):  
Luis Vallejo, Jose Mora, Dong-Nhat Nguyen, Jan Bohata, Vicenç Almenar, Stanislav Zvanovec, Beatriz Ortega, "On the 40 GHz Remote versus Local Photonic Generation for DML-based C-RAN Optical Fronthaul" (3<sup>rd</sup> meeting)
- Czech Technical University in Prague (CZ), Universitat Politecnica de Valencia (ES):  
Jan Bohata, Luis Vallejo Beatriz Ortega, Stanislav Zvanovec, "Optical fiber and wireless fronthaul for 5G NR seamless transmission" (4<sup>th</sup> meeting)

Publications:

- (ES/CZ) L. Vallejo, J. Mora, D.-N. Nguyen, J. Bohata, V. Almenar, S. Zvanovec, B. Ortega, "On the 40 GHz Remote Versus Local Photonic Generation for DML-Based C-RAN Optical Fronthaul," in Journal of Lightwave Technology, vol. 39, no. 21, pp. 6712-6723, 1 Nov.1, 2021, doi: [10.1109/JLT.2021.3102818](https://doi.org/10.1109/JLT.2021.3102818).
- (CZ/ES/UK) J. Bohata, D.-N. Nguyen, J. Spacil, M. Komanec, B. Ortega, L. Vallejo, Z. Ghassemlooy, S. Zvanovec, "Experimental comparison of DSB and CS-DSB mmW formats over a hybrid fiber and FSO fronthaul network for 5G," Opt. Express, vol. 29, no. 17, p. 27768, Aug. 2021, doi: [10.1364/OE.434334](https://doi.org/10.1364/OE.434334).