Working Group 3, Milestone M3.2

VLC and FSO systems implementation and evaluation

This document is based upon work from COST Action NEWFOCUS

Introduction

Based on the overall goal of NEWFOCUS WG3, which was to develop practical high-reliability (i) visible light communication (VLC)-based solutions for use in smart-cities (vehicular communications, etc.) and underwater communications and (ii) high data rate point-to-point FSO links for deployment in backhaul/fronthaul infrastructures, Milestone 3.2 has been successfully accomplished, as demonstrated in the internal documents discussed in the project meetings as well as publications, see the list below.

In the following, results for **experimental implementation, evaluation and demonstration of the following systems** are presented:

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

1. Vehicular Communications

VLC-based vehicular networks have been experimentally demonstrated, and their performance under weather and environmental conditions, ambient noise and link misalignments have been experimentally investigated.

1.1 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).

1.2 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, pp. 2751, Apr. 2021, doi: 10.3390/s21082751.

2. Optical Camera Communications

Optical Camera Communications for mid-range transmission spans have been validated for wireless sensor networks within the NEWFOCUS framework.

2.1 Internal documents

- IDeTIC Universitad de Las Palmas (ES), Czech Technical University in Prague (CZ):

"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. Advances in exposure-related ISI equalization" (5th meeting).
- Czech Technical University in Prague (CZ), IDeTIC Universitad de Las Palmas (ES), Northumbria University (UK): Improved bandwidth performance of hybrid optical wireless communication for an IoT environment (7th meeting).

2.2 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.
- (ES/CZ) V. Matus, V. Guerra, C. Jurado-Verdu, S. Zvanovec, J. Rabadan and R. Perez-Jimenez, "Design and implementation of an optical camera communication system for wireless sensor networking in farming fields," 2021 IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Helsinki, Finland, 2021, pp. 1-6, doi: 10.1109/PIMRC50174.2021.9569653.
- (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.
- (ES/CH) V. Matus, S. R. Teli, C. L. Aguiar, J. Rabadan, S. Zvanovec and R. Perez-Jimenez, "A practical teaching tool for optical camera communications," 2023 17th International Conference on Telecommunications (ConTEL), Graz, Austria, 2023, pp. 1-6, doi: 10.1109/ConTEL58387.2023.10198924.

3. Outdoor FSO/VLC Links/Networks

Software-defined implementations of real-time multiple-input multiple-output free space optical links with adaptive switching have been demonstrated. In addition, FSO systems have been characterized experimentally under fog and turbulence conditions.

3.1 Input documents

- Northumbria University (UK), Czech Technical University in Prague (CZ): Performance Analysis and Software-Defined Implementation of Real-Time MIMO FSO With Adaptive Switching in GNU Radio Platform (3rd meeting).
- 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), Czech Technical University in Prague (CZ), Institut Fresnel (FR): Demonstration of An Optical Wireless Communication System using a Software-Defined Ecosystem (5th meeting).
- Northumbria University (UK), Czech Technical University in Prague (CZ): Implementation and Evaluation of a 10 Gbps Real-time FSO Link (7th meeting).

- Czech Technical University in Prague (CZ), German Aerospace Center (DE): Influence of ASE noise from EDFAs on a free-space QKD channel (9th meeting).

3.2 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.
- (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.
- (UK/CZ) Z. Htay, Z. Ghassemlooy, S. Zvanovec, M. M. Abadi and A. Burton, "An Experimental Testbed for Implementation and Validation of Software defined FSO under Atmospheric Conditions using USRPs," 2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), Porto, Portugal, 2022, pp. 59-64, doi: 10.1109/CSNDSP54353.2022.9908057.
- (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.
- (UK/CZ/FR) Z. Htay, C. Guerra-Yánez, B. Karanam, Z. Ghassemlooy, S. Zvanovec, M.-A. Khalighi and M. M. Abadi, Demonstration of Optical Wireless Communications System Using a Software Defined Ecosystem, 2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), Porto, Portugal, 2022, pp. 836-840, doi: 10.1109/CSNDSP54353.2022.9907956.
- (CZ/ES/UK) C. Guerra-Yánez, A. Mederos-Barrera, S. Zvánovec and Z. Ghassemlooy, "Experimental Evaluation of a Hierarchical QAM VLC System," 2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), Porto, Portugal, 2022, pp. 545-549, doi: 10.1109/CSNDSP54353.2022.9907925.
- (UK/CZ) Z. Htay, C. Guerra-Yánez, Z. Ghassemlooy, S. Zvanovec, M.M. Abadi and A. Burton, Experimental Real-time GbE MISO FSO Under Fog Conditions with Software Defined GNU Radio Platform-based Adaptive Switching, Journal of Optical Communications and Networking, vol. 14, issue 8, pp. 629-639, 2022: DOI: 10.1364/JOCN.458562.

4. Microwave Photonics Links for Radio-over-Fiber and FSO Communications

The incoming networks and standards, e.g., 5G and beyond, necessitate the use of high frequency bands, i.e. millimeter wave (mmWave), which poses considerable challenges in the design and implementation of electrical devices and circuits at high frequencies. These challenges can be addressed by adopting a number of technologies such as radio-over-fibre (RoF), radio-over-free space optics (RoFSO), and hybrid RoF-RoFSO, where the RF signal is transmitted over an optical communication link with minimum losses compared to the coaxial cables or radio frequency wireless transmission. This approach is considered in the fronthaul solution in a mobile radio access network (RAN). Moreover, photonics can also be exploited

to generate high frequency signals with significant savings in terms of requirements for electrical components and costs, so different schemes have been proposed and implemented for mmWave signal generation in future hybrid networks.

In this regard, NEWFOCUS consortium members have been working in these areas and demonstrated experimental results from RoFSO systems for transmission of mmWave signals as part of 5G and beyond wireless networks. In these works, different modulation techniques for use in microwave photonics have been investigated with experimental results on the performance of RoFSO and RoF links under atmospheric channel conditions i.e., more specifically turbulence. In addition to tests and measurements carried out in outdoor environments, the research groups have carried out a number of laboratory-based evaluations for RoFSO links at 40 and 60 GHz and over a 100 m link span in order to demonstrate enhanced mobile broadband capabilities while keeping a flexible RAN.

4.1 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 (2nd meeting).
- KTH Royal Institute of Technology (SE), Riga Technical University (LV), Directly modulated quantum cascade laser and its application in free-space communications (3rd meeting).
- Universitat Politecnica de Valencia (ES), Czech Technical University in Prague (CZ): "On the 40 GHz Remote versus Local Photonic Generation for DML-based C-RAN Optical Fronthaul" (3rd meeting).
- Czech Technical University in Prague (CZ), Universitat Politecnica de Valencia (ES): "Optical fiber and wireless fronthaul for 5G NR seamless transmission" (4th meeting).
- Czech Technical University in Prague (CZ), Universitat Politecnica de Valencia (ES), Northumbria University of Newcastle (UK): A Scalable 26 GHz RoF Relay System using Optoelectronic Extender (7th meeting).
- Universitat Politecnica de Valencia (ES), Czech Technical University in Prague (CZ): Phase Modulation-based Fronthaul Network for 5G mmWave FR-2 Signal Transmission over Hybrid Links (7th meeting).
- Czech Technical University in Prague (CZ), Universitat Politecnica de Valencia (ES): "Centralized full-duplex photonic mmW fronthaul link based on phase modulation", (8th meeting).

4.2 Publications

- (ES/CZ) L. Vallejo, J. Mora, D.-N. Nguyen, J. Bohata, V. Almenar, S. Zvanovec and 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.
- (CZ/ES/UK) J. Bohata, D.-N.Nguyen, J. Spacil, M.Komanec, B. Ortega, L. Vallejo, Z. Ghassemlooy and 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.
- (ES/CZ) L. Vallejo, B. Ortega, D. -N. Nguyen, J. Bohata, J. Mora and S. Zvanovec, "Multiband IFoF signal transmission based on DML with local photonic 40 GHz up conversion," 2021

17th International Symposium on Wireless Communication Systems (ISWCS), Berlin, Germany, 2021, pp. 1-5, doi: 10.1109/ISWCS49558.2021.9562239.

- (CZ/ES/UK) J. Bohata, D. Nhat Nguyen, Z. Ghassemlooy, B. Ortega and S. Zvánovec, "The Evaluation of an RoF System Using FSO and a Seamless Antenna Link for the 5G RAN," 2021 17th International Symposium on Wireless Communication Systems (ISWCS), Berlin, Germany, 2021, pp. 1-5, doi: 10.1109/ISWCS49558.2021.9562212.
- (SE/DK/CN) X. Pang, O. Ozolins, S, Jia, L, Zhang, R, Schatz, A, Udalcovs, V, Bobrovs, H. Hu, T. Morioka, Y.- T. Sun, J. Chen, S. Lourdudoss, L. K. Oxenløwe, S. Popov and X. Yu, "Bridging the Terahertz Gap: Photonics-assisted Free-Space Communications from the Submillimeter-Wave to the Mid-Infrared, in Journal of Lightwave Technology, vol. 40, no. 10, pp. 3149-3162, 2022, doi: 10.1109/JLT.2022.3153139.
- (SE/LV/CN/FR) X. Pang, R. Schatz, M. Joharifar, l. Udalcovs, V. Bobrovs, L. Zhang, X. Yu, Y.-T. Sun, G. Maisons, M. Carras, S. Popov, S. Lourdudoss and O. Ozolins, “Direct Modulation and Free-space Transmissions of Up to 6 Gbps Multilevel Signals with A 4.65-µm Quantum Cascade Laser at Room Temperature,” in Journal of Lightwave Technology, vol. 40, no. 8, pp. 2370-2377, 2022, doi: 10.1109/JLT.2021.3137963.
- (CZ/ES/US/JP) D.-N. Nguyen, L. Vallejo, V. Almenar, B. Ortega, P. T. Dat, S. T. Le, J. Bohata and S. Zvanovec, “Full-duplex transmission of multi-Gb/s subcarrier multiplexing and 5G NR signals in 39 GHz band over fiber and space,” Applied Optics, vol. 61, no. 5, pp. 1183-1193, 2022. , doi: 10.1364/AO.447529.
- (CZ/ES) J. Bohata, L. Vallejo, B. Ortega and S. Zvánovec, "Optical CS-DSB Schemes for 5G mmW Fronthaul Seamless Transmission," in IEEE Photonics Journal, vol. 14, no. 2, pp. 1-7, April 2022, Art no. 5521407, doi: 10.1109/JPHOT.2022.3161087.
- (CZ/UK) J. Bohata, D.-N. Nguyen, J. Spáčil, D. Suslov, D. Dousek, S. Zvánovec, Z. Ghassemlooy and M. Komanec, “Performance Evaluation of Seamless 5G Outdoor RoFSO Transmission at 39 GHz,” IEEE Photonics Technology Letters, vol. 34, no.1, pp. 7-10, 2022. doi: 10.1109/LPT.2021.3134559.
- (ES/CZ) L. Vallejo, J. Bohata, D. -N. Nguyen, B. Ortega, J. Mora and S. Zvánovec, "Heterogeneous RoF, RoFSO and RF bidirectional links in n79 5G band," 2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), Porto, Portugal, 2022, pp. 16-20, doi: 10.1109/CSNDSP54353.2022.9908007.
- (CZ/ES) J. Bohata, D.-N. Nguyen, P. T. Dat, Z. Ghassemlooy, B. Ortega and S. Zvanovec, “A Scalable 26 GHz RoF Relay System using Optoelectronic Extender,” IEEE Photonics Technology Letters, , vol. 35, pp. 293-296, 2023“ doi: 10.1109/LPT.2023.3241438.
- (ES/CZ) M. Botella-Campos, J. Bohata, L. Vallejo, J. Mora, S. Zvanovec and B. Ortega, "Phase Modulation-based Fronthaul Network for 5G mmWave FR-2 Signal Transmission over Hybrid Links," 2023 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), Gothenburg, Sweden, 2023, pp. 282-286, doi: 10.1109/EuCNC/6GSummit58263.2023.10188257.
- (ES/CZ/UK) L. Vallejo, B. Ortega, J. Mora, D.-N. Nguyen, C. Guerra, J. Bohata, J. Spacil and S. Zvanovec, “Demonstration of M-QAM OFDM Bidirectional 60/25 GHz Transmission over 10 km Fiber, 100 m FSO and 2 m Radio Seamless Heterogeneous Fronthaul Link,” Optical Fiber Technology, vol 77, 103161, 2023. Doi: 10.1016/j.yofte.2022.103161.