COST CA 19111

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

Deliverable D1.1

Channel Modeling and Transceiver Design for Ultra-Short range Optical Wireless Links

Date: 27/04/2023

Edited By:

Luis Nero Alves (Instituto de Telecomunicações, Aveiro, Portugal)

Pranciskus Vitta (Vilnius University, Faculty of Physics, Lithuania)

This document is based upon work from COST Action NEWFOCUS,
supported by COST (European Cooperation in Science and Technology)

List of contributors

Name	Country
Erich Leitgeb	AT
George-Iulian Uleru	RO
Gurgen Mardoyan	AM
Hoa Le Minh	UK
Hovik Baghdasaryan	AM
Hristo Danchov Ivanov	AT
Latif Ladid	LU
Oussama Haddad	FR
Jahid Hasan	FR
Ali Khalighi	FR
Luis Nero Alves	PT
Luis Rodrigues	PT
Marian Marciniak	PL
Mircea Hulea	RO
Mónica Figueiredo	PT
Othman Younus	UK
Pasha Bekhrad	AT
Sujan Rajbhandari	UK
Tamara Hovhannisyan	AM
Tamara Knyazyan	AM
Thomas Kamalakis	GR
Tigran Baghdasaryan	BE
Vaigai Nayaki Yokar	UK
Zabih Ghassemlooy	UK

This document is based upon work from COST Action NEWFOCUS,
supported by COST (European Cooperation in Science and Technology)

1. Introduction

As part of NEWFOCUS network, WG1 - Ultra-short-range links has the overall goal to develop Point-to-Point and high performance Optical Wirelesss communications OWC based solutions for ultra-high-speed links for sub-metre applications. Towards this goal the major tasks are: T1.1- Channel modelling and characterization for application oriented scenarios with particular focus on optical front-end characteristics; T1.2- Design of innovative PHY layer solutions including MIMO structures; T.1.3- Upper layer design coping with QoS constraints and T1.4- Design and assessment of compact, energy-efficient and high-performance PoC demonstrators for optical interfaces and short-range high data-rate VLC systems. For the current reporting period, deliverable D1.1 on Channel Modeling and Transceiver design, reports the major findings communicated by the MC members contributing to this group.

2. State of the art

WG1 focuses on the transmission of sub-meter communication links, such as intra- and inter-chip communication, high-performance computing platforms, and device-to-device communication in dense IoT scenarios. Recent research has shown that OWC is a promising technology for these types of scenarios. Free Space Optical (FSO) interconnects, such as FSOIs in integrated circuit and printed circuit board designs, provide higher speeds with low energy consumption per bit compared to metal interconnects. Optical devices, including multiple quantum well modulators/detectors and vertical cavity surface-emitting lasers (VCSELs), have been proposed as solutions for inter-chip connectivity [1]. FSOIs offer several advantages, such as higher capacity and design flexibility, mitigation of routing and switching issues, and reduced electromagnetic interference. They can also be used in high-performance computing platforms and intra-satellite systems. However, there is a lack of focused research direction in this field, and several scientific and technical issues need to be addressed, such as beam wandering and occlusion due to temperature effects and dust-induced signal dispersion, as well as cross-link interference with wavelength reuse in line-of-sight and/or diffused optical transmission configurations. While wavelength division multiplexing and multiple-input multiple-output techniques have been explored to increase data throughput at the physical layer, there have not been many reported research works on media access control and upper network protocol layers. OWC also presents unique opportunities for short-range, hyper-dense IoT applications that require reliable connections between smart objects with sensing/actuating and communication capabilities. RF technologies may struggle with these requirements, making OWC an attractive option. Ongoing research is focusing on establishing reliable OWC links for low-power, resource-constrained devices, mobility issues such as fast pointing and fading mitigation, and inexpensive and seamless integration of transmitters and receivers in wireless sensor-based infrastructure.

3. Recent achievements

The following sections report the recent achivemnst on WG1 arising from inpou document contributions by MC mebers showing interest in WG1. Contributions focus On the targeted goals for the reporting period, aiming at contributions on channel modeling and PHY layer design considerations, respectively, tasks T1.1 and T1.2. Sections 3.1 and 3.2 focus on channel availability for sensor networks in general and wireless body area networks (WBAN) for medical applications. Sections 3.3 to 3.6 report findings on PHY layer transceiver design, for diverse applications (IoT, device-to-device

This document is based upon work from COST Action NEWFOCUS,
supported by COST (European Cooperation in Science and Technology)

communications, chip-to-chip communications and spiking neural networks for sensing applications). Finally, section 3.7 highlights the usage of the Ipv6 Standard for device-to-device communcations.

3.1. Wireless Sensor Network Optimization

Within WG1, we have undertaken a series of studies to determine the viability of optical wireless-based sensor networks. Wireless sensor networks (WSNs) are currently being deployed in everyday objects to collect and transmit information related to humidity, temperature, heartbeat, motion, etc. Such networks are part of the massive machine-type communication scenario (mMTC) within the fifth/sixth generation of wireless networks. We consider the optimization and design of an optical WSN composed of multiple battery-powered sensor nodes based on light-emitting diode transmitters.

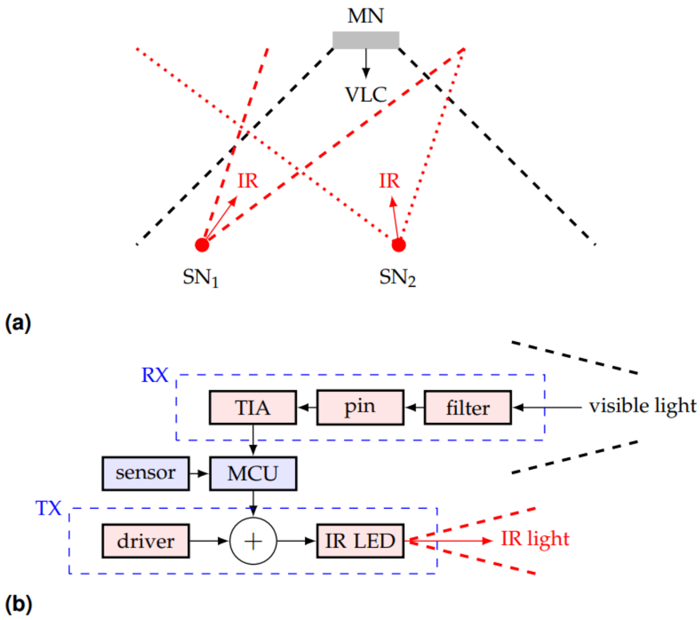


Figure 1: Proposed hybrid VLC/IR system architecture.

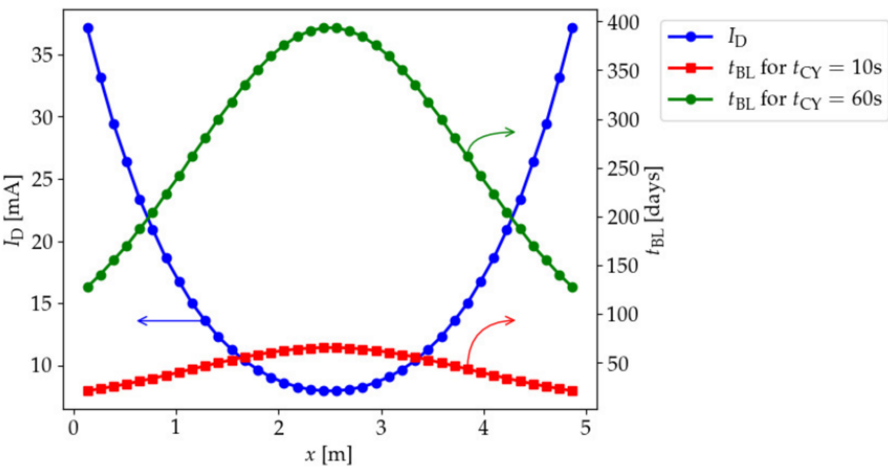


Figure 2: Required driving current and battery life for a typical indoor environment obtained with the proposed VLC/IR system architecture.

This document is based upon work from COST Action NEWFOCUS, supported by COST (European Cooperation in Science and Technology)

Optical wireless communications (OWC) covering the infrared and visible part of the spectrum are being considered as part of future 5G/6G enabling technologies in certain applications, where RF-based system is not the preferred option. Typical applications include smart manufacturing information proclaiming to the public, underwater IoT, intelligent transportation, agriculture and smart health-care. OWC-based WSN may offer higher data throughputs, inherent security, lower energy usage. However, due to the limitations of line-of-sight (LOS), energy-efficient network models and routing protocols must be used. Figure 1 shows the basic architecture of a proposed VLC/IR system that can be used for future WSNs. Figure 2 shows the battery life and the required driving current for the IR uplink. More details can be found in the publications [2] and [3]. The code developed within this deliverable is also available on Github (https://github.com/thomaskamalakis/pyowiot)

3.2. Performance Analysis of Multiple Access m-CAP for Optical-Based Intra-WBAN Links

Optical-based wireless body area networks (WBANs) are a promising solution for remote monitoring of vital signs in radio-frequency sensitive environments such as healthcare facilities. When dealing with a large number of sensors coexisting within the same vicinity, multiple access (MA) solutions are necessary to manage the simultaneous access to the medium. This contribution investigated the use of MA multi-band carrierless amplitude and phase (m-CAP) for intra-WBAN links. Using the outage probability criterion, we evaluated the performance of such a solution while accounting for realistic statistical channel models. For this, we considered a model of a patient walking inside a hospital room. A star network topology was considered with 10 sensor nodes (SN), which are connected to a coordinator node (CN), placed on the patient shoulder. Also, we considered an accurate representation of the body parts by taking a 3D mesh representation of the patient's body, as shown in Fig. 3 (left) Furthermore, we studied the impact of system parameters such as bandwidth, number of sub-bands, and roll-off factor β on the link performance. For instance, Fig. 3 depicts (right) the output power versus the sum rate (i.e., the whole WBAN data rate, assuming equal rate for all SN-CN links) for a range of SNs, Pt = 50 mW, and different values of β. We noticed, an improved performance with increase in β, that can be explained by the reduced ICI for higher β. Overall, the presented results suggest using mCAP as a promising scheme with acceptable implementation complexity in the considered application scenarios.

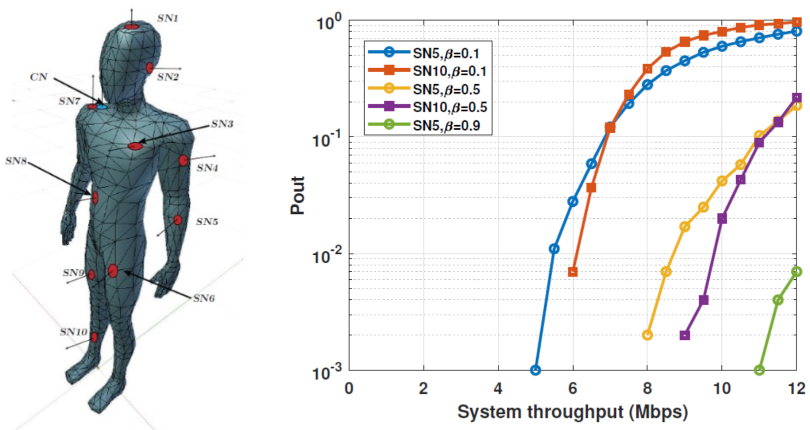


Figure 3: Intra WBAN system setup (left), Intra WBAN achieved results.

This document is based upon work from COST Action NEWFOCUS,
supported by COST (European Cooperation in Science and Technology)

33. Experimental validation of analog m-CAP receivers for Internet of Things

This study offers an experimental validation of m-CAP modulation, where the transmitter (Tx) is performed in the digital domain and the receivers (Rxs) are created using an analogue homodyne Rx architecture, whose implementation is based on a low cost/power approach. The experimental setup is implemented as shown in Figure 4 which includes the following components: (a) optical emitter; (b) optical receiver; (c) homodyne receiver, which includes multipliers and filters for I and Q; and (d) system platform, which consists of an FPGA with one DAC and one ADC. The system platform was used to create the necessary tools to test and validate the implemented analogue Rx while also performing m-CAP modulation. The implemented printed circuit boards (PCB) are shown in Figure 5 and Figure 6. The eye diagrams for I and Q were obtained for *d* of (1.4, 1.7, 2, 2.3) m, and for θ = 0°, which are shown in Figure 7. As expected, the eye is more closed with the increasing *d*, degrading the noise margin. The constellations for *d* = {1.4, 1.7, 2.0, 2.3} m, are depicted in Figure 8, along with the reference constellation for QAM. A total of 5000 symbols were considered for each *d* and the constellations were normalized to 1 W per symbol. As expected, the dispersion in the constellation symbols increases with *d*, where the best performance is observed at shorter *d*. The error vector magnitude (EVM) in terms of the root mean square (RMS) and peak value is shown in Table 1 to better assess the constellation's quality.

Table 1 - EVM analysis

Distance (d) [m]	1.4	1.7	2.0	2.3
RMS [%]	12.3	16.4	21.8	27.4
Peak [%]	35.3	43.9	58.5	79.7

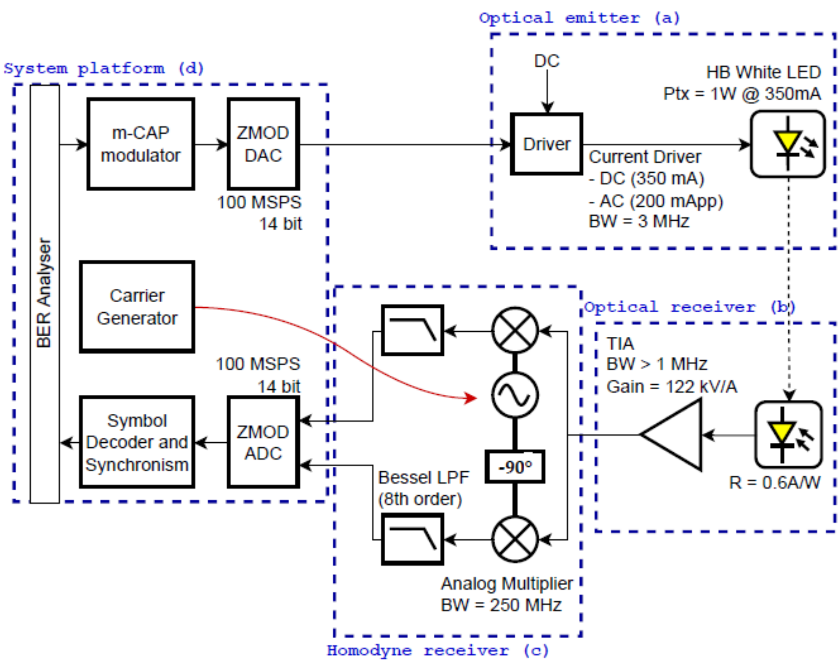


Figure 4: System block diagram: (a) optical emitter, (b) optical receiver, (c) homodyne receiver, and (d) system platform.

This document is based upon work from COST Action NEWFOCUS,
supported by COST (European Cooperation in Science and Technology)

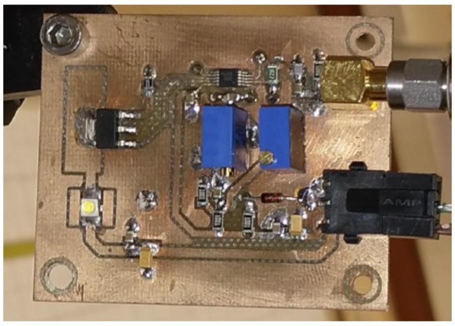


Figure 5: VLC LED driver circuit.

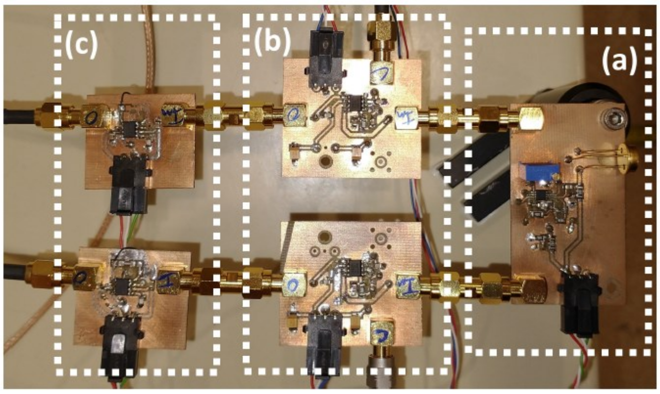


Figure 6: Implemented Rx circuit: (a) optical frontend with amplification, (b) analogue multipliers, and (c) analogue filters.

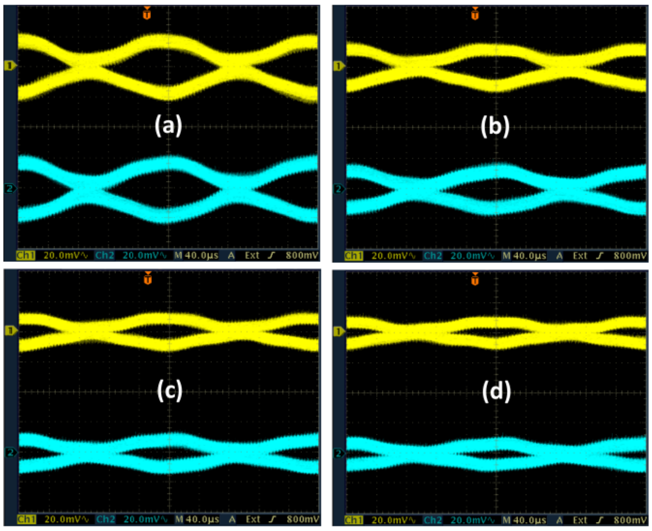


Figure 7 - Eye diagrams for I (yellow) and Q (blue) components for different d (a) 1.4 m, (b) 1.7 m, (c) 2 m, and (d) 2.3 m. Vertical scale: 20 mV/div, horizontal scale: 40 µs.

This document is based upon work from COST Action NEWFOCUS,
supported by COST (European Cooperation in Science and Technology)

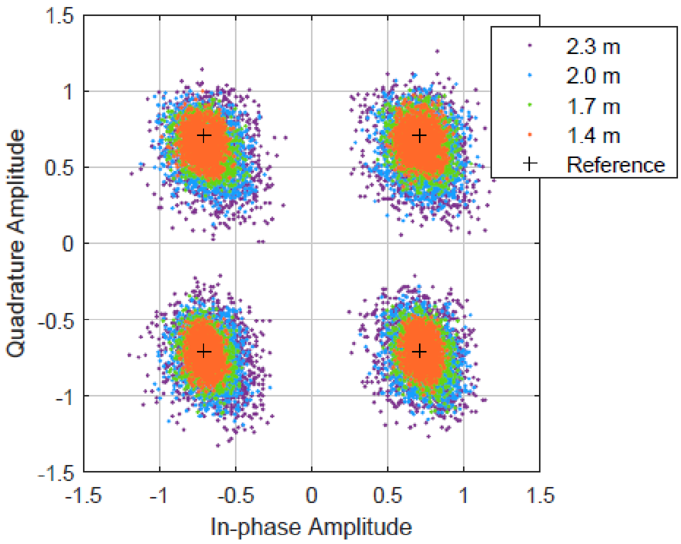


Figure 8 - Rx constellations for d of 1.4, 1.7, 2.0 and 2.3 m

3.4. Data Rate Enhancement using CNN in Smartphone-to-Smartphone Visible Light Communication

Visible alternative wirelesss communication to the radio frequency (RF)-based technology. There are several advantages of VLC, including light communication (VLC) is a subset of optical wireless communication (OWC), which provides an a lower cost, lower bandwidth congestion, and greater energy efficiency. Thus, VLC can complement existing wireless technologies and provides a practical alternative to conventional wireless communication techniques [4-7]. Based on the application and data rate requirements, VLC can use either photodetector-based receivers or image sensor-based receivers. VLC using camera-based receivers are best known as optical camera communications (OCC), which is developed within the IEEE P802.15.7a standard working group [7]. In recent years, modern cameras have become much more powerful, not only for photography but also for a wide range of visual detection and digital data collection in many daily applications [8-9]. Therefore, the smart phones cameras could be utilized for low-rate data transmission, localization and sensing as well as imaging [5][6]. Therefore, for data communication an encoded image (in the form of Quick Response (QR) and American standard Code for Information Interchange (ASCII)) is emitted from the transmitting phone to the receiving phone. Thus the concept of in the context of smartphone-to-smartphone visible light communication (S2SVLC) [10]. Note that, QR and ASCII images provide a secure communication link alternative to traditional RF-based Bluetooth, Wi-Fi, and Near Field communication schemes. VLC-OCC is mainly for very low data transmission due to the limited frame rates of standard cameras. Using a dedicated two-dimensional code on the screen in S2SVLC that uses the cellular overlap-based resource allocation concept a data throughput of up to 225 kbps could be achieved, which is considerably high in OCC [11]. Although many modern smartphones have high-quality cameras, not all cameras are manufactured the same way, and not all can capture barcode data accurately or rapidly. However, adjusting the screen's brightness and contrast does lead to improved visibility of barcodes.

S2SVLC have several issues including (i) the use of specialized code, that cannot be detected and decoded by some devices since they do not have the required software or hardware; (ii) synchronization between the transmitter and camera-based receiver; (iii) blurry images being transmitted and received due to the mobility of the transmitter and the receiver, which causing motion blur and pixel

This document is based upon work from COST Action NEWFOCUS, supported by COST (European Cooperation in Science and Technology)

superimposition; and (iv) the accuracy of decoding being dependent on the location and surrounding environments with varying levels of lux [4][6].

A convolutional neural network (CNN) is a type of artificial neural network that has gained considerable attention in recent years due to their ability to improve the processing of image categorization, recognition, segmentation, classification, and other tasks [9]. Hence, to overcome the issues described above, one could adopt a CNN-based machine learning model that acts as a non-blind blur restoration technique to restore blur levels in S2SVLC system. In this case the information is transmitted using ASCII and QR codes, which are readily supported by Android and iOS platforms, while the machine learning model is developed in Python using TensorFlow Keras framework, which can be imported into Android studio. Based on the proposed model, S2SVLC links can be classified with greater than 97% accuracy using QR and ASCII codes. Furthermore, a significant improvement in the data rate and accuracy of 324 kbps over 32 kbps can be achieved.

Through the transmission of the robust control frame, CNN algorithms are used to estimate the offset between the screen and the camera in such a system. In order to make predictions about how a system will behave in the future, a CNN model could be trained with augmented images in order to identify patterns or trends. This information could be used to adjust the behavior of each device or sensor, thereby improving the system's synchronization. Thus, the proposed lightweight model can improve classification, synchronization, practicality, and detection performance. Due to the limited processing power and memory resources of smartphones, CNNs are challenging to use in smartphone communication applications. In order to run efficiently on smartphones, CNNs are computationally intensive and may require specialized hardware or software optimizations. In spite of this, recent advances in mobile hardware and the proposed lightweight model have made it possible to run CNNs on smartphones in a highly energy efficient and high performance manner.

3.5. Chip-to-Chip Communication by means of Electro-Optical Modulator

Nowadays, photonic technologies target solving challenges of modern and future optical short-distance interconnects. Different types of optical interconnects for inter/intra chip links are under development [13,14]. Optical interconnection has obvious and significant advantages over electrical counterparts for chip-to-chip connection with high bit rates and absence of electromagnetic interference. A key element of short-distance optical links is electro-optical modulator (EOM). In our joint work we analyzed transmission-type multi-nanolayer EOM for chip-to-chip optical interconnection. Numerical analysis is performed by the method of single expression [15]. Transmission type of Fabry-Perot resonant EOM consisting of electro-optical material of LiNbO3 (spacer) covered by thin conducting nano-layers of Indium-tin-oxide (ITO) material embedded between Si/SiO2 distributed Bragg reflectors (DBRs) is considered. Two semi-transparent conducting ITO nano-layers of the multi-nanolayer structure of EOM serve as electrodes for applying electrical signal to the electro-optical material. The DBRs are repetitive bilayers of different optically transparent materials of quarter-wavelength thickness and possess the highest reflectance at the central wavelength in the middle of the stop-band. From four types of possible alternations for bilayers of DBRs the suitable structure has been chosen [16]. DBRs are symmetrical regarding the spacer and the layers adjacent to the spacer are of higher permittivity, while outer layers are of lower permittivity. The structure of EOM with this type of DBRs provides the highest value of transmittance and a high finesse that is crucial for the operation of a transmission-type modulator. As an external light source, a conventional laser diode at 1.55 μm wavelength is considered. Efficiency of optical wave intensity modulation of EOM is analysed by means of influence of permittivity change of electro-optical material under applied voltage on the resonator's maximal transmission peak shift. As it follows from the numerical analysis the shift of the peak is proportional to the increase of the spacer

This document is based upon work from COST Action NEWFOCUS, supported by COST (European Cooperation in Science and Technology)

thickness and change of spacer's permittivity. To be close to practical realization the thickness is chosen approximate to 1 mm. An influence of the change of EOC's permittivity on the resonant peak shift is studied as well. An essential peak shift is observed at the change of EOC's permittivity in the range of 10^{-4}. Substantial change of the transmittance of the modulator structure will be suitable for efficient on-off keying. The Fabry-Perot type resonant electro-optical modulating structure with DBR mirrors and conducting layers serving for electrical signal application is suggested. The nano-layered structure with the spacer of EOC of thickness $d_{EOC} \approx 1\,\text{mm}$ will permit to obtain the necessary shift of the transmittance peak suitable for digital communication. This type of electro- optical modulator will be useful for chip-to-chip optical short link.

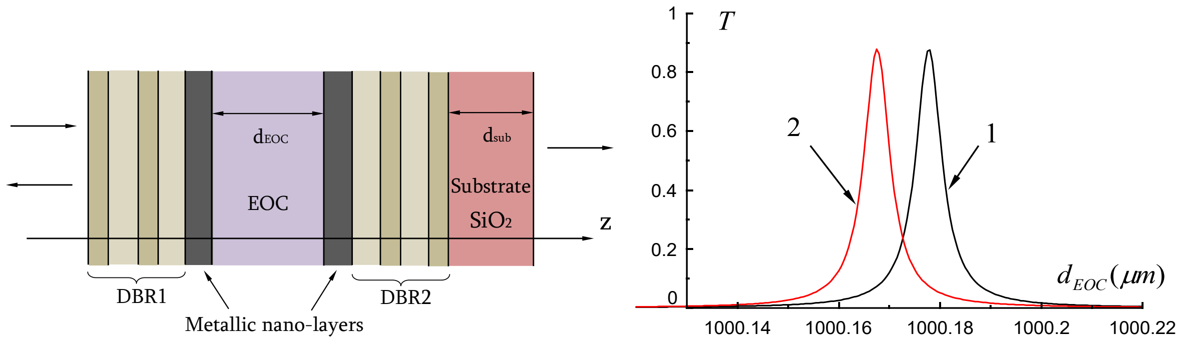
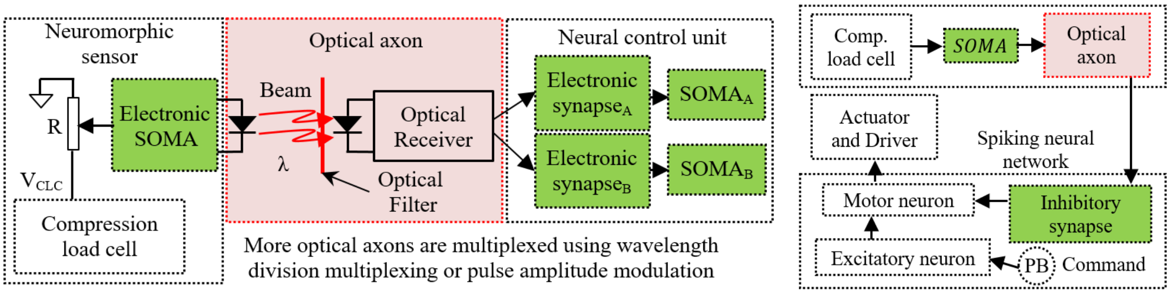


Figure 9: Transmission-mode Fabry-Perot electro-optical modulator considered in the work (left). Shift of transmission peak at the change of EOC's permittivity (1. $\varepsilon_{EOC} = 4.89$, 2. $\varepsilon_{EOC} = 4.8901$) (right).

3.6. Neuromorphic Sensors with Visible Light Communication

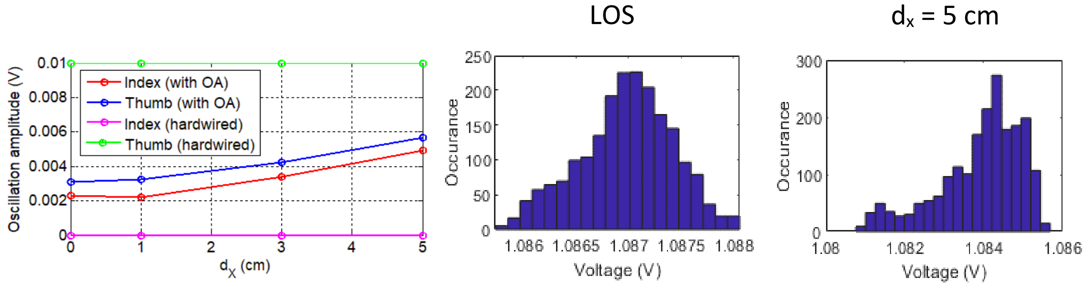
Spiking neural networks (SNN) can control single-joint robotic arms' precise rotation and force when shape memory alloy (SMA) actuators are used. For the purpose of controlling anthropomorphic fingers, SNN receives feedback from neuromorphic sensors, which usually respond to the flexion angle and the force applied to the fingertips. The robotic fingers and hands are in relative motion with the robot's body, which typically includes the main unit for the limb's motion control. Due to the motion of the robotic hands the distance and alignment between the neural modules can vary significantly from a few millimetres to tens of centimeters considering the length of the human arm. An elegant method to implement the connection between the neural control unit (NCU) and the neuromorphic sensors on limbs is to use visible light communication technology. Here we evaluated for the first time the optical wireless connections between neuromorphic sensors and spiking neural networks (SNN) for implementing the NCU [17]. The optical connections are based on the recently introduced optical axons (OA) that allows parallel communication between neurons while being tolerant to the beam fading effect on the transmission of the synaptic weights. As presented in Fig. 9, the neuromorphic sensors converts a physical measure (i.e., compression force) into a voltage V_{CLC} and then into optical pulses that activates the corresponding synapses through the OA.

This document is based upon work from COST Action NEWFOCUS,
supported by COST (European Cooperation in Science and Technology)



(a) (b)

Figure 9: (a) The structure of the neuromorphic sensors with visible light communication; and (b) the structure of the SNN that regulates the force of the fingers.



(a) (b)

Figure 10: The results showing: (a) the variation of the sensors output with the deviation from the line of sight (LOS); b) histograms of the output of the CLC connected to the index finger when optical receiver is placed in the LOS and maximum deviation, respectively.

A method to implement parallel operation of OAs is wavelength division multiplexing (WDM) when a wavelength is allocated to each neuromorphic sensor to stimulate the corresponding neural paths in the SNN.

Fig.10 illustrates the comparison of the electro-optical SNN with and without optical axons when the robotic hand moves relative to the NCU that regulates the force applied to the fingers. The evaluation was done during steady-state by determining $V_{\mathrm{CLC-max}}$, which increases with deviation d_X from LOS as presented in Fig. 10 (a). We determine the histograms of V_{CLC} for several values of d_x starting from LOS in order to provide an in-depth analysis of the regulatory regime, see examples in Fig. 10 (b). Both evaluations show that, the OA affects the regulatory performance of the SNN at certain levels of channel attenuation. However, the robotic arm is still capable of holding onto an object even during steady state, despite the small oscillations in the finger force during steady state.

Further research is conducted to determine whether pulse amplitude modulation (PAM) can be used to achieve parallel-like operation of optical axons that connect both neuromorphic sensors and actuator drivers to the NCU [18]. By using an optical reference channel, the gain of the optical receiver is dynamically adjusted to improve decoding performance when the NCU is moving relative to the sensors. The experiments demonstrate that the electro-optical SNN with PAM is capable of controlling the fingers and hold an object under different channel conditions. Although additional hardware is needed to improve the performance of the PAM-based system, the preliminary results of both studies indicate that PAM is less tolerable to the misalignment of the optical channels than WDM. The future

This document is based upon work from COST Action NEWFOCUS, supported by COST (European Cooperation in Science and Technology)

investigation will focus on the benefits of each method of implementing parallel neural paths in electro-optical SNN based on the findings of this early studies.

3.7. IPv6 for IoT Device to Device Communications

IPv6 (Internet Protocol version 6) is the latest Internet protocol ratified back in December 1998 with RFC2480 and updated with RFC8200 in July 2017 that provides a unique identifier for every device on the internet. It is designed to replace the current IPv4 protocol, which has limitations due to the limited number of unique addresses it can provide. The current Internet Protocol version 4 (IPv4) has run out of routable address space back in February 2011, the new Internet Protocol version 6 (IPv6) comes with a virtually unlimited address spaces with 2 to the power of 128 (340 Trillion Trillion Trillion) address space restoring thereby the end to end model offering routable address space for applications like true end to end IoT to scale. The use of new IPv6-based technologies such as Multicast (BIERv6) and Segment Routing over IPv6 (SRv6) enhances further the deployment of IoT, unlocking new applications such as Blockchain-based IoT technology that can be extended to various social and economic solutions in trade and food supply chain management, financial services, manufacturing, art and media, smart cities, property and title transfers, management of the integrity of transactions, and improving the quality of healthcare while reducing the risk of errors, as well as many others.

Kevin Ashton coined the Internet of Things back in 1998 on the basis of the RFID research done at MIT. RFID is up to day not yet connected directly to the Internet since RFID does not have any capacity to have an IP stack let alone an IPv6 stack. In this case, IoT has started as a “fake news” that created a buzz for all researchers to do research in non-IP IoT protocols such as BackNet, KNX and LoRa which have moved slowly to adopt the IP Protocols. LoRa has been very successful in its non-IP and IPv4 deployment and has now adopted IPv6.

When it comes to IoT (Internet of Things) device-to-device communication, IPv6 has several advantages over IPv4. IPv6 supports auto-configuration, which means that IoT devices can be configured automatically without the need for manual intervention.

Furthermore, IPv6 offers improved security features, including support for IPSec, which can encrypt and authenticate network traffic. This is especially important for IoT devices that transmit sensitive data, such as medical information or financial data.

The deployment of IPv6 has reached 2.5 billion IPv6 users worldwide which is some 50% v6 penetration. The number one country is China with 700 M followed by India with 350 M, Total Europe with 140 M and the US with 120 M then Brazil with 60 M, Japan 45 M.

Asia counts for more than 60% total of IPv6 deployment.

The driving force behind these efforts has been the IPv6 Forum created back in 1999 by the pioneers and inventors of IPv6 in the IETF IPv6 Task Force: https://www.ipv6forum.com/

In summary, IPv6 is an ideal protocol for IoT device-to-device communication due to its larger address space, auto-configuration capabilities, and improved security features. As the number of connected devices continues to grow, IPv6 will become increasingly important for ensuring the efficient and secure operation of IoT networks.

This document is based upon work from COST Action NEWFOCUS,
supported by COST (European Cooperation in Science and Technology)

4. Conclusions

This deliverable presented the contribitutions received within the framework of WG1 for the tasks T1.1 and T1.2, reporting on channel modeling and Transceivers for PHY layer design. This working group had few contributions when measured by the number of submitted input documents and published joint papers. This reflects the satus of the deliverable, which his limited in extent but able to cover part of the WG1 goals for this reporting period.

5. References

[1] D.A.B. Miller, “Device Requirements for Optical Interconnects to Silicon Chips,” Proceedings of the IEEE, vol. 97, no.7, July 2009.
[2] T. Kamalakis, Z. Ghassemlooy, S. Zvanovec, L. N. Alves, and M. Khalighi, “Optimization and design of a diffuse optical wireless sensor network,” Appl. Opt., vol. 61, no. 22, pp. 6599–6608, Aug. 2022.
[3] T. Kamalakis, Z. Ghassemlooy, S. Zvanovec, and L. N. Alves, “Analysis and simulation of a hybrid visible-light/infrared optical wireless network for IoT applications,” J. Opt. Commun. Netw., JOCN, vol. 14, no. 3, pp. 69–78, Mar. 2022.
[4] M. B. Rahaim, A. M. Vegni and T. D. C. Little, "A Hybrid Radio Frequency and Broadcast Visible Light Communication System", Proc. IEEE GLOBECOM 2011 vvksos., pp. 792-96, 2011-Dec.-5–9.
[5]J.-P. Javaudin, "OMEGA ICT Project: Towards Convergent Gigabit Home Networks", Proc. IEEE PIMRC 2008, pp. 1-5, 2008-Sept.-15–18.
[6] V. N. Yokar, Hoa-Le-Minh, F. Ghassemlooy and W. L. Woo, "A Novel Blur Reduction Technique For QR And ASCII Coding In Smartphone Visible Light Communications," 2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), 2022, pp. 428-433, doi: 10.1109/CSNDSP54353.2022.9907993.
[7] R. Boubezari, H. Le Minh, Z. Ghassemlooy and A. Bouridane, "Smartphone Camera Based Visible Light Communication," in Journal of Lightwave Technology, vol. 34, no. 17, pp. 4121-4127, 1 Sept.1, 2016.
[8] L. Feng, R. Q. Hu, J. Wang, P. Xu and Y. Qian, "Applying VLC in 5G Networks: Architectures and Key Technologies," in IEEE Network, vol. 30, no. 6, pp. 77-83, November-December 2016, doi: 10.1109/MNET.2016.1500236RP.
[9] Q. Wang, M. Zhou, K. Ren, T. Lei, J. Li and Z. Wang, "Rain Bar: Robust Application-Driven Visual Communication Using Color Barcodes," 2015 IEEE 35th International Conference on Distributed Computing Systems, 2015, pp. 537-546.
[10] M. Stafford, A. Rogers, S. Wu, C. Carver, N. S. Artan and Z. Dong, "TETRIS: Smartphone-to-Smartphone Screen-Based Visible Light Communication," 2017 IEEE 14th International Conference on Mobile Ad Hoc and Sensor Systems (MASS), 2017, pp. 570-574.
[11] Hao, Tian, Ruogu Zhou and Guoliang Xing. “COBRA: color barcode streaming for smartphone systems.” MobiSys '12 (2012).
[12] J. Chen and X. Ran, "Deep Learning With Edge Computing: A Review," in Proceedings of the IEEE, vol. 107, no. 8, pp. 1655-1674, Aug. 2019, doi:10.1109/JPROC.2019.2921977.
[13] W. Liu, et al., Exploration of Electrical and Novel Optical Chip-to-Chip Interconnects. IEEE Design & Test, 31 (5), p. 28-35 (2014).
[14] H.V. Baghdasaryan, M. Marciniak, T.M. Knyazyan,"Optical Interconnects – Prospective Alternative for High-Speed Inter/Intra-Chip Galvanic Links", IEEE EWDTS, Yerevan, p. 48-50, September 7-10, 2007.
[15] H.V. Baghdasaryan, T.M. Knyazyan, “Problem of plane EM wave self-action in multilayer structure: an exact solution”, Optical and Quantum Electronics, vol. 31, no.9/10, pp. 1059-1072, 1999. Doi: 10.1023/A:1007024312874.
[16] H.V. Baghdasaryan, T.M. Knyazyan, T.H. Baghdasaryan, B. Witzigmann, and F. Roemer, “Absorption loss influence on optical characteristics of multilayer distributed Bragg reflector: wavelength-scale analysis by the method of single expression”, Opto−Electronics Review, vol. 18, issue 4, pp. 438–445, 2010. Doi: 10.2478/s11772-010-0049-0.

This document is based upon work from COST Action NEWFOCUS, supported by COST (European Cooperation in Science and Technology)

[17] M. Hulea, G. -I. Uleru, O. I. Younus, S. Rajbhandari and Z. Ghassemlooy, "Neuromorphic Sensors with Visible Light Communications," *2022 4th West Asian Symposium on Optical and Millimeter-wave Wireless Communications (WASOWC)*, Tabriz, Iran, Islamic Republic of, 2022, pp. 1-5, doi: 10.1109/WASOWC54657.2022.9798428.
[18] G. -I. Uleru, M. Hulea, O. I. Younus, Z. Ghassemlooy and S. Rajbhandari, "Pulse Amplitude Modulation for Electro-optical Spiking Neural Networks," *2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP)*, Porto, Portugal, 2022, pp. 584-588, doi: 10.1109/CSNDSP54353.2022.9908009.

This document is based upon work from COST Action NEWFOCUS, supported by COST (European Cooperation in Science and Technology)