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Contents

1. **Introduction** 2

2. **Optical Camera Communications -** *Z. Ghassemlooy, S. Zvanovec, L. N. Alves, R. Perez-Jimenez, O. I. Younus, S. R. Teli, and V. Matus* 4

3. **Atmospheric State Information for Long-range FSO Communication –** *N. Doelman, E. Udvary, Y. Ata, S. Häusler, T-C Bui, and L. Scheers* 8

4. **Audio Signal Quality Assessment in Visible Light Communication - –** *J. Galić, M. Mlađen, G. Gardašević, M. Petković, B. Malčić, and S. Šajić* 12

5. **Physics-based Modelling of LEDs and Phosphors Paves the Way to Boost VLC Performance -** *J-P Linnartz and P.Salvador* 15

6. **Current Status and Possible Directions to Gain Momentum in the Massive Adoption of OWC-** *A. A. Dowhuszko, I. Tavakkolnia, and P. D. Diamantoulakis* 18

7. **Quantum Communications over Free Space Optical Satellite Links: Challenges and Opportunities-** *A. A. Dowhuszko, C. Guerra-Y´anez, V. K. Papanikolaou, M. Galambos, T. Cavdar, N. Doelman, F. Moll, P. Kleinpaß, D. Orsucci, I. de Marco, G. T. Djordjevic, B. Batagelj, M. Safari, and S. Zvanovec* 22

8. **Optical Technology for Joint Communication and Sensing –** *S. A. Tegos, V. K. Papanikolaou, E. Aparicio-Esteve, E. Skaljo, P. Louro, E. Panayirci, and P. D. Diamantoulakis* 26

INTRODUCTION

The current wireless technologies cannot sustain the explosion of the wireless date traffic related to the emerging applications with new requirements of massive connectivity, enhanced reliability, low latency, a wide range of data rates, intelligence and adaptability, security, energy and spectrum efficiencies and sustainability. In addition, increasing demand for massive data traffic is accompanied by the growing requirements for full coverage and heterogeneous networks, with high transmission data rates, ultra-low-latency and ultra-high reliability. Therefore, the next generation of wireless communication systems, i.e., the sixth generation (6G) wireless networks, must address this by considering all possible technologies that utilise all the available frequency spectrums including optical bands; advanced physical and network layers solutions; energy harvesting; massive distributed cell-free multiple-input-multiple-output architectures; blockchain and quantum communication technologies; and integration of terrestrial and non-terrestrial communications enhanced with artificial intelligence (AI) and machine learning (ML). Furthermore, 6G networks will support new classes of services, such as: (*i*) green and sustainable communication for terrestrial, non-terrestrial and underwater scenarios; (*ii*) joint sensing, localisation and communications capabilities; (*iii*) reconfigurable and adaptable communication networks using reconfigurable metasurfaces; (*v*) five-sense communication; (*vi*) digital twin and virtual and augmented reality; and (*vii*) Internet-of-Things and Internet-of-Everything. In addition, as part of the 6G transition from data-oriented to task-oriented communication, AI/ML-based technologies and architectures will be developed to accelerate the integration of technologies (i.e., enabling sensing, positioning, and communication capabilities), network optimization, and security and privacy in various application scenarios. It is anticipated that millimetre wave, THz and optical wireless technologies, with greater bandwidth and denser distribution of massive antenna arrays, will play crucial roles in next generation wireless networks.

The EU COST Action on Future Generation Optical Wireless Communications (NEWFOCUS) aim has been to explore radical solutions that could significantly influence the design and implementation of future wireless communication networks[1]. **NEWFOCUS** set out to achieve this aim by bringing together researchers, scientists and engineers from EU and beyond to address the new challenges associated with **optical wireless communication (OWC)** covering all three spectrum bands (i.e., ultraviolet, visible and infrared) and to establish it as a complementary technology to the radio frequency-based wireless systems in order to meet the demanding requirements of the fifth generation and the future sixth generation backhaul and access networks. To achieve these, NEWFOCUS research programme was carried out under two major pillars:

> *The development of OWC-based solutions capable of delivering ubiquitous, ultra-high-speed, low-power consumption, highly secure, and low-cost wireless access in diverse application scenarios. The developed solutions supporting Internet-of-Things for smart environments with applications in vertical sectors.*
>
> *The development of flexible and efficient backhaul/fronthaul OWC links with low latency and compatible with access traffic growth.*

NEWFOCUSE activities were designed around (*i*) four technical work packages based on the ultra-short, short, medium and long transmission ranges; (*ii*) special interest group on emerging topics; (*iii*) technical meetings, workshops, conferences, short term scientific mission, and training schools to maximise networking possibilities; and (*iv*) white papers and roadmaps.

The first two White Papers were on the use of OWC as an enabling technology in a range of areas outlined in under Pillar II; and for medium- and long-range links in terrestrial, space-to-ground and ground-to-space, inter-satellite, and underwater communications. The focus of this final **White Paper** on **Optical Wireless Communication** is on current status and possible directions. There are eight contributions covering Optical Camera Communications; Atmospheric State Information for Long-range FSO Communication; Audio Signal Quality Assessment in Visible Light Communication; Physics-based Modelling of LEDs and Phosphors Paves the Way to Boost VLC Performance; Current Status and Possible Directions to Gain Momentum in the Massive Adoption of OWC; Quantum Communications over Free Space Optical Satellite Links: Challenges and Opportunities; and Optical Technology for Joint Communication and Sensing.

We would like to thank you all authors for their contributions to this White Paper, which we hope will serve as a valuable resource on some of the features, challenges, and future work associated with the OWC technology.

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[1] https://www.newfocus-cost.eu/action/

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Optical Camera Communications

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I. INTRODUCTION

There are several applications that drive the use of digital cameras, including smart cities, smart devices and phones, intelligent transportation systems, robotics, medical, visual surveillance systems, among others. The image sensor (IS) market was valued at over $26 billion in 2022 and is projected to reach $~38.6 billion by 2027 [1]. The utilization of IS has not only revolutionized the paradigm of capturing and sharing images and videos but also has extended its application in data transmission, sensing, tracking, and positioning as well as into integrated sensing-positioning-communications. **Visible light communications (VLC)** employing light emitting diodes (LEDs) as transmitters and complementary metal-oxide-semiconductor ISs (or cameras) as receivers is best known as **optical camera communications (OCC)** since 2010. In recent years, we have seen growing research and development activities in VLC-OCC technology as a promising solution for the next generation of wireless communication networks (i.e., sixth generation and beyond). More specifically, the availability of ISs in pervasive consumer electronics has created significant opportunities for the practical application of VLC-OCC by offering many interesting features as outlined in Fig. 1(a).

The practical applications of VLC-OCC using cameras with a resolution on the order of megapixels are best used in low data Internet-of-Things (IoT) and Internet-of-Everything (IoE) in applications, see Fig. 1(b). Systems like QR codes and augmented reality allow people to access additional content in the virtual realm using their smart devices. Additionally, OCC uses advanced image processing for shape recognition and estimating depth perception [2], [3]. OCC can also be used for indoor positioning with higher accuracy (sub-centimeter). For example, 3D positioning is achieved using dual cameras on smartphones to capture images, whereby determine the distance from the light source to the receiver by comparing the disparity of corresponding projection point from each camera. RF-based technologies such as WIFI, Bluetooth and near-field communications are currently used with limited transmission capabilities [4].

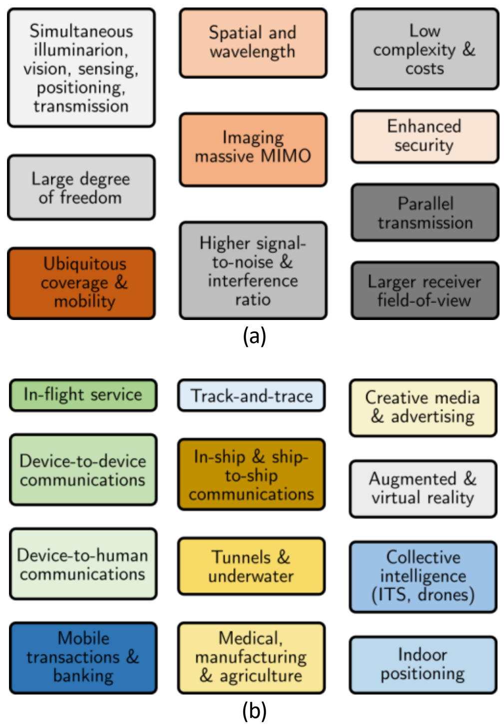

Fig. 1. VLC-OCC: (a) key features, and (b) typical applications.

The typical camera consists of a two-dimensional array of photodetector pixels that can classify multiple spatially separated light sources with a high level of accuracy. The devices are comprised of an imaging lens, an IS, colored filters, and a readout circuit for capturing images in the form of single or multiple frames and converting them into intensity (grayscale) values based on the region of interest partitioning and pixel sampling. The integrated image processor uses a demosaicing algorithm taking advantage of the built-in color filter array such as a Bayer filter to produce a colored output image, which acts as the data image for subsequent post-processing. Background lights can be easily suppressed by using band-pass optical filtering in conjunction with frame differential techniques. The **IEEE 802.15.7m** [5] outlines a standard that supports OCC functionalities and medium access control modifications.

II. STATE OF THE ART

In the ISs there are two modes of operation (i) *global shutter* – where an array of sensors is simultaneously exposed, with each pixel's information being read out sequentially. Using this mechanism, high-quality images and moving objects can be captured and processed; and (ii) *rolling shutter* – where pixels in a column-by-column format or in a row-by-row format are sequentially exposed to the light to create an image. With the rolling shutter mode, the receiver can sample at higher rates, which results in increased data rates, enabling multiple LED states (ON/OFF) to be captured at the same time, where the captured image contains a collection of black and white stripes representing LED flickering. Note that the captured strip widths and their numbers are determined by the modulation frequencies and the distance between the camera and the light sources, respectively. The maximum symbol rate of commercial cameras is typically less than 15 sps, which is insufficient for some applications due to their low frame rates (i.e., about 30 frames per second). In addition, in RS-based OCC, the data rate is dependent on the camera's pixel clock, frame rate, and exposure time. The first two parameters are directly dependent on the IS technology, whereas the latter, defining the bandwidth of OCC, can be controlled by the user. Therefore, the shorter the exposure time, the higher the bandwidth. Note that short exposure times, however, result in low signal-to-noise ratios (SNR) and, consequently, higher bit error rates (BER). To reduce image processing time (i.e., latency), a combination of an automatic location-based system and an efficient segmentation algorithm can be used.

As part of OCC, the region of interest is critical for identifying the communication region of bright and dark stripes, which directly impacts both the demodulation and decoding of the captured images into digital format. Complex algorithms are required for decoding optical information into digital data. Note, in OCC, data evaluation can be performed using image processing tools in the software domain (i.e., MATLAB, OpenCV and Python). Furthermore, low frame rates result in flickering, which is not desirable since the critical flicker frequency is usually 100 Hz for human eyes. Low frame rate OCC systems can use both standard modulation schemes (e.g., on-off keying, frequency shift keying and multi-carrier modulation) as well as signage cipher modulation for integrating data communication with cinematic contents and digital advertising, colour shift keying (CSK), optical spatial modulation, multilevel intensity modulation, distance colour-coded on-off keying [6-8]. Of these, CSK has received the most attention for enhancing the transmission data rate and was originally proposed for VLC in the IEEE 802.15.7 standard. For short-range IoT applications, reliable, robust, flicker-free and low data rates (few kbps) OCC links are more important than the high-speed system. However, to increase the data rate, a multiple-input multiple-output (MIMO)-OCC system using an array of red, green and blue LEDs is one possible option, see Fig. 2.

Equalization is needed to compensate for distortions experienced by the propagating optical signals over the free space channel. Several techniques have been proposed and utilized in OCC including (*i*) an artificial neural network equalizer; (*ii*) predictive equalization to deal with changing light intensity; and (*iii*) double-equalization to deal with spatial and time dispersions. In OCC, noise increases with the sensitivity setting in the camera, the exposure time, temperature and even varies amongst different camera models. In digital cameras there are three types of noise sources: (i) *random noise* (short exposure time and high ISO sensitivity) – This is characterized by fluctuations in intensity and color above and below the actual intensity of the image; (ii) *fixed pattern noise* (low ISO sensitivity and long exposure time) - Because the intensity of a pixel is far greater than that of the ambient random noise fluctuations; and (iii) *banding noise* (high ISO sensitivity) - This is a highly camera-dependent feature, which is introduced by the camera when it reads data from the IS.

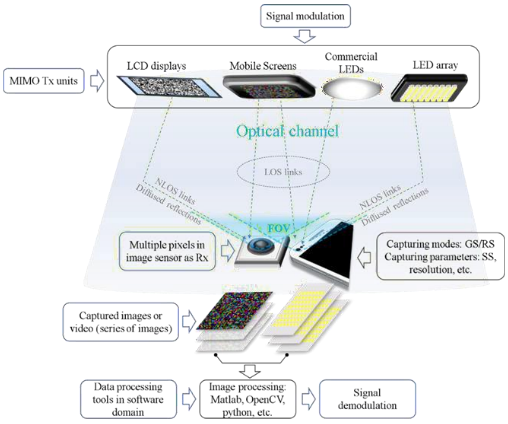

Fig. 2. MIMO-OCC.

III. CHALLENGES AND FUTURE WORKS

OCC offers many appealing features; however, the nature of image-based communications still poses several challenges associated with the devices design, advanced signal processing, interference suppression and system/network protocol designs. These include:

- *New system models* – Most models are based on photodiode receivers, which do not truly represent the IS-based receiver. It should also consider (*i*) interference and noise due to solar irradiance, streetlights and advertising boards, which will degrade the performance seriously, and even cause saturation and blinding of the IS; and (*ii*) the effects of radiation interference, atmospheric conditions, presence of suspended particles in the air and the temperature variation.
- *Nonlinearity induced distortion* – During the design, optimization and practical implementation processes of intensity modulation VLC-OCC links, the nonlinearity of light sources (LEDs and screen pixels) must be compensated using pre-distortion mechanisms and gamma-correction avoidance.

- *Synchronization* – This is an essential component of OCC systems, just as it is in digital transmission, particularly when dealing with high-frame-rate cameras and asynchronous protocols, which require careful design to ensure accurate data transmission. Therefore, a dedicated protocol with a timestamp for alignment between the transmitter and receiver is needed. Such a protocol must be scalable and adaptable to various OCC setups. It is also necessary to adjust the data payload size by designating additional bits for synchronization based on the synchronization requirements.
- *Energy usage* – This is typically higher for cameras compared to a photodetector, thus shorter battery life.
- *New topologies and routing algorithms* – To achieve large-scale VLC-OCC networking.
- *Data throughput* - OCC systems have relatively low data throughput due to the low frame rates of common cameras. which is inversely proportional to the exposure time (i.e., the exposure duration per frame of the IS). High frame rate cameras can be used to increase the throughput but are costly.
- *Broadcast transmission mode* - Existing OCC systems transmit data in this way, only allowing reception of the transmitted data provided that the receiver is within the field of view of the transmitter. In addition, it is challenging to establish bidirectional communication.
- *Blurring and blooming effects* - (*i*) Internal electrical noise, photon overflow and external ambient light lead to fringes blurring, where bright and dark fringes are difficult to distinguish with the increasing distance that need addressing to achieve longer range; (*ii*) while upper limits of exposure and camera gain values cause blooming effects with over exposed incident light on image pixels; and (*iii*) due to a camera not being focused leading to signal-to-noise ratio degradation and poor spatial separation of source signals.
- *Blocking/shadowing and atmospheric conditions* - Further research is needed to determine the impact of these on the performance of OCC links. Consequently, developing an adaptive OCC link could provide one option for dynamically adjusting the communication path or signal strength based on the environment.
- *Integrated sensing, positioning and communication technology* – This offers two primary advantages over dedicated sensing, positioning and communication links: (*i*) integration gains - from the efficient use of congested wireless/hardware resources; and (*ii*) coordination gains - to balance multiple-functional performance or the execution of mutual assistance.

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Atmospheric State Information for Long-range FSO Communication

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I. INTRODUCTION

Long-range **free-space optical** (FSO) communication links are strongly affected by the state of the atmospheric medium. Phenomena such as optical turbulence, cloud coverage, wind, sky radiance, precipitation, fog and haze, aerosols all have an impact on the free-space optical wave propagation and distortion. The composite of these phenomena comprises the overall atmospheric state. In this paper, we will denote knowledge of the FSO-relevant atmospheric quantities by the term *Atmospheric State Information* (ASI).

In the design and analysis of contemporary FSO communication links it is quite common to use general and static models of the atmospheric state quantities. Examples are the HV-57 model for the optical turbulence C_n^2-profile, a Kolmogorov turbulence spectrum, and fixed values for wind speed, visibility and background noise. In practice, the atmospheric state quantities are both location-specific and time-variant. Moreover, the fluctuations of these quantities over time and space can be significant. This implies that the fluctuations of FSO link performance can be similarly significant. This is illustrated for the distribution of received intensity values of an FSO beam in Fig. 1. Both the mean and the variance of the distribution strongly vary with C_n^2 value.

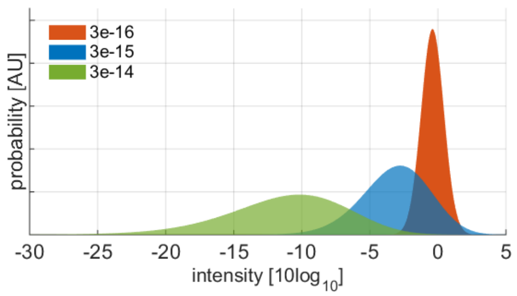

Fig. 1. Probability distributions of received, turbulence-induced intensity fluctuations in an exemplary 5 km horizontal FSO link for various C_n^2 values.

In regular FSO communication, detailed information on optical turbulence and attenuation (by clouds and aerosols) is crucial. On top of that, in photon-starved conditions, the background sky radiance plays a critical role. This applies to deep-space communication and (wireless) **quantum key distribution** (QKD). Whereas in regular optical communication the signal can be amplified in order to achieve a sufficient signal-to-noise ratio (SNR), in QKD, the transmitted signal must be a single photon or a weak coherent pulse with a low mean photon number. Depending on the protocol a specific threshold for the quantum bit error rate (QBER) can be defined, above which it is no longer possible to generate a key. In Fig. 2 this effect is illustrated, and it shows the strong dependency of QBER on the background radiation level.

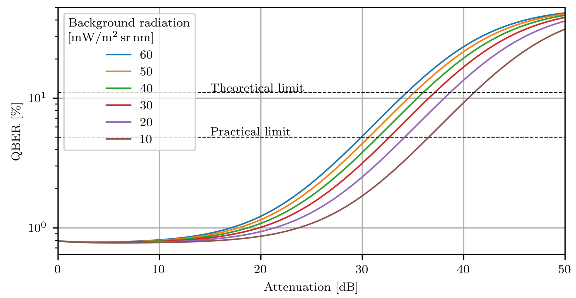

Fig. 2. Dependency of QBER and attenuation for different background radiation levels in an exemplary QKD scenario [1].

II. RECENT ADVANCES IN MODELING AND MEASUREMENTS

This Section focuses on two critical atmospheric quantities: optical turbulence and background radiation.

Optical turbulence – spatial power spectrum modelling

The performance evaluation of FSO communication systems requires an accurate characterization of optical turbulence. One aspect of optical turbulence is its power spectrum, which describes how the turbulence energy is distributed across different spatial frequencies. Among the several power spectra models such as Kolmogorov, Tatarskii, von Kármán and Modified atmospheric models, the most widely used theoretical model is the Kolmogorov turbulence model.

It should be noted that the Kolmogorov power spectrum model is valid in inertial sub-range and it assumes that the turbulence is isotropic, homogeneous, the outer scale length is infinite and the inner scale length is zero. However, in real outdoor conditions, atmospheric turbulence does not always follow Kolmogorov model, due to various factors such as temperature gradients, wind shear, or other environmental conditions. When the turbulence deviates from Kolmogorov model, it is referred to as non-Kolmogorov turbulence and its spectrum Φ_n is given by:

$$\Phi_n(k,\alpha) = A(\alpha)C_n^2\kappa^{-\alpha}, 3<\alpha<4 \quad (1)$$

where κ is the spatial wave number and α is the power law exponent, scaling factor $A(\alpha)=\Gamma(\alpha-1)cos(\alpha\pi/2)/(4\pi^2)$ with Γ the gamma function and C_n^2 is the generalized refractive index structure function.

Optical turbulence - C_n^2 modelling and prediction

Turbulence modelling amounts to solving the Navier-Stokes equations that govern fluid flow on the small spatial and temporal scales at which turbulence takes place. The computational burden involved in doing this gave rise to meso- and microscale modelling schemes that effectively decrease the computational demand at the cost of fidelity. In these modelling schemes, the turbulence is explicitly resolved on larger spatial scales, while a simplified turbulence model is used to represent the turbulent processes taking place at smaller spatial scales. By combining such a physics-based turbulence model with a physically or statistically-based C_n^2 parametrization, a mesoscale or microscale C_n^2 model can be obtained.

Particularly mesoscale C_n^2 modelling continues to demonstrate its potential to the optics community for hind- and forecasting purposes ever since its first introduction in 1995 by Bougeault et al. [2]. It remains however associated to a relatively large computational demand and is hindered by uncertainties in the physics parametrization. Recently, an ensemble technique has been proposed to cope with the latter by incorporating the uncertainties in an ensemble C_n^2 prediction, which was shown to outperform individual C_n^2 predictions [3]. In addition, machine learning (ML) techniques also show potential in reducing such uncertainties by improving the C_n^2 parametrization. Together with the ever-increasing computational resources ML techniques can have the added benefit of reducing the computational cost, thereby opening a pathway for fast and meaningful C_n^2 profile predictions.

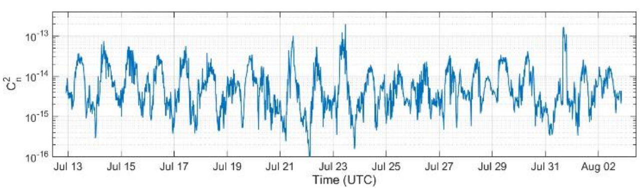

Fig. 3. Measured C_n^2 values at ground level during a 3 weeks field test with an optical feeder link, Cabouw NL in 2022 [4].

Optical turbulence – test campaigns

Recent field tests of FSO links provide further insight into the spatial and temporal properties of optical turbulence. An illustration of the dynamic behavior of C_n^2 is given in Fig. 3, which shows a variation in C_n^2 values larger than a factor 100. These measurements apply to ground-level behavior, whereas for FSO links a full, C_n^2 profile as a function of altitude is required. Therefore, the European space agency (ESA) has initiated a multi-year test campaign for three European sites; see ESA project ANAtOLIA.

Background sky radiance – measurement equipment and campaigns

Background light received by an FSOC telescope may originate from solar and lunar sky radiance, stars and planets, zodiacal light, airglow and diffuse emission in the galaxy, reflections on the surface of the transmitter device, channel crosstalk and anthropogenic light. When knowing the environmental input parameters, the background light caused by solar sky radiance can be simulated for daylight and cloud-free sky scenarios with tools like MODTRAN or libRadtran. Practical conditions which differ from this scenario need to be analyzed experimentally [1].

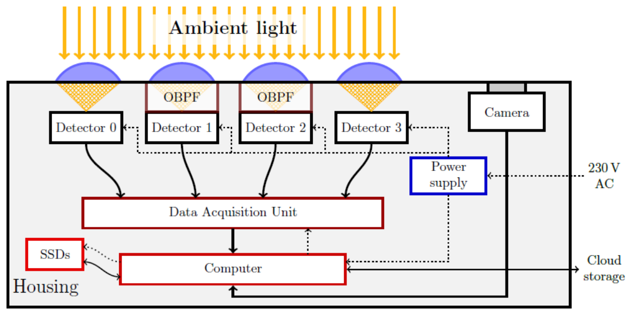

Fig. 4. Block diagram of the background light measurement station.

The Budapest University has developed a portable ambient light measurement set-up [5] to perform measurements in distinct locations without cumbersome dis- and reassembly processes. The optical power values are measured in four wavelength ranges (around 1550nm: typical classical free space optical channel, 810nm: possible future optical quantum channel, visible total, near-infrared total), all equipped with a lens, a photodetector, and optionally optical and electrical filters. Fig. 4 represents the functional block diagram of the measurement set-up.

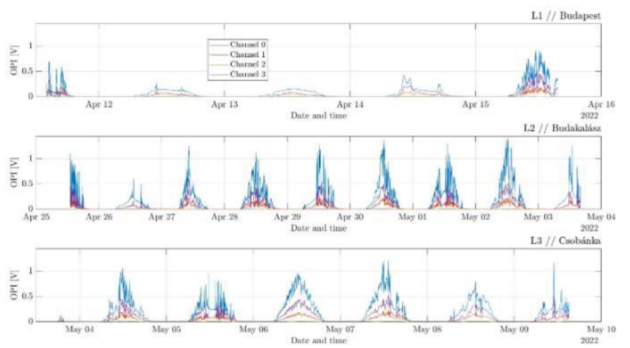

Fig. 5. Measured background sky radiation over several days and 3 locations in Hungary [5].

The resultant data in Fig. 5 show that a clouded sky has two adverse effects simultaneously. It attenuates the signals between the ground station and the satellite and increases the amount of noise to the receiver. The clouds are also responsible for a rapidly varying SNR. Dark rain clouds can effectively block most of the sunlight. The measured amount of noise in the 1540nm infrared channel is low compared to that in the 810nm channel; this meets the expectations based on the sun's emission.

III. CHALLENGES AND OUTLOOK

Developments for ASI (models, methods and technology) in FSO communication are now underway, partially based on earlier developments for astronomical instrumentation. This Section will describe needs and further advancements in knowledge and technology of atmospheric state quantities.

Optical turbulence – spatial power spectrum modelling

Three optical turbulence phenomena require further study: the non-Kolmogorov spectrum, anisotropy and intermittency. Although evidence of non-Kolmogorov turbulence incorporating anisotropy has been shown experimentally [6], the viability of this model and the physical meaning of the power law exponent α require further investigations. Also, the anisotropic behavior of turbulence, needs to be examined in terms of physical mechanisms such as wind shear, thermal gradients and atmospheric stratification. Finally, the intermittency of turbulence should be taken into account to arrive at a more accurate, dynamic characterization.

Optical turbulence - C_n^2 modelling and prediction

Mesoscale or microscale methods – possibly ML-assisted – are regarded as a potential game changer for obtaining location-specific and time-variant C_n^2 in FSOC. Specific advancements are however needed with respect to:

1. Uncertainties in the physics parametrization and parametric representation of unresolved processes.
2. Reduction of the computational demands, which is particularly relevant for nowcasting and forecasting purposes.
3. The availability of measured data for validation purposes. There is a particular need for upper atmosphere and day-time data.

Optical turbulence – measurement equipment

FSO communication requires low volume and cost equipment capable of monitoring during day- and night-time, handling weak to strong turbulence conditions. A potential concept is the portable '24-hour Shack-Hartmann Image Motion Monitor' [7].

Background sky radiation

Current simulation tools – solving the radiative transfer equation – are limited to cloud-free skies and rural environments. An extension towards (partial) cloud coverage and urban environments is desirable. Complementary measurement campaigns on background radiation are necessary to collect more data in various weather conditions and seasons and at diverse locations.

The measurement set-up described in Section II is planned to be upgraded to better read night-time optical power levels. This can be achieved by using advanced electrical noise reduction systems, a highly precise analog-to-digital converter and the exact optical elements (telescope, filters, etc.). A major improvement is expected by using superconducting nanowire single-photon detector (SNSPD) technology, which is under development.

FSO link perspective

A very useful description of ASI aspects on optical link level is provided by the CCSDS [8]. This recommended practice describes all relevant atmospheric quantities plus specifications on measurements and derivations. From an operational perspective, the role of ASI can be further detailed along the various 'phases' of FSO Communications. We can distinguish the following 4 phases:

a) OGS site assessment and selection
b) FSOC system design
c) Real-time operations and decision making
d) FSO link scheduling

For these phases, the merits of relevant ASI quantities, can be summarized as shown in Table 1.

Table 1. Merits of ASI quantities in four FSOC phases.

phase	ASI type	Optical Turbulence		Background radiation	Attenuation	
		Cn2 profile Fried parameter isoplanatic angle	Wind profile coherence time		clouds	aerosols
OGS site assessment	historical, statistical	medium	low	medium	high	high
FSOC system design	historical, statistical	high	high	high	high	high
Real-time operation	nowcast, actual	high	high	high	high	high
FSO link scheduling	forecast	medium	low	medium	high	high

In this overview, past, present and future atmospheric states are required. Statistical ASI would enable a 'probabilistic' FSOC system design approach, in which the uncertainty in the atmospheric quantities is fully accounted for. In doing so, the time-variant performance behavior and reliability of the FSO link can be optimized.

Actual ASI enables the implementation of adaptive transmission schemes and facilitates condition monitoring procedures during real-time operation of FSOC. Forecasting ASI allows for the preparation of link-handovers – for instance switching between optical ground stations and/or space terminals - when the atmospheric conditions would necessitate that.

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Audio Signal Quality Assessment in Visible Light Communication

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I. Introduction

The continuous increase in the amount of traffic in the radio frequency (RF) spectrum requires the exploration of new spectrum parts that can provide faster, more reliable, and more efficient data transmission. In comparison to RF communications, **visible light communication** (VLC) has the potential to accommodate more users and provide significantly higher data rates per user due to its enormous bandwidth available for data transmission. The frequency range of visible light (VL) is between 400 THz and 800 THz; therefore, VL has 10,000 times the range of radio waves. The VLC implies the emission of highly directed and limited VL, thus enabling the coexistence of many non-interfering communication links in close proximity.

In the ever-expanding range of possible VLC applications, the transmission of audio signals remains a fundamental type of communication with a broad range of specific and interdisciplinary research areas. Audio signals include all types of sounds in frequency range from 20 Hz to 20 kHz. They carry significant and relevant information and play an important role in our daily communication (interpersonal communication, entertainment, perception of the environment, etc.). Modern approaches for acoustical signal enhancement include echo canceling, acoustic feedback and active noise control, dereverberation, noise suppression, spatial filtering, and audio-visual signal enhancement [1].

The assessment of audio quality is an important step in modern communication systems design. Subjective and objective measures are available for that purpose. Since subjective assessments are time-consuming and expensive, objective measures gained more attention in research studies. Some of the most significant methods include:

- Total harmonic distortions (THD)
- Intermodulation distortions (IMD)
- Signal-to-noise ratio (SNR)
- Signal-to-noise and distortion (SINAD).

The most favorable measure that gives an estimate of the subjective difference grade of an audio signal is the perceptive evaluation of audio quality (PEAQ). The main purpose of PEAQ is to give an estimate of the audio quality of a tested audio device. PEAQ achieves this by comparing the input and output audio signals of the device, resulting in a quality score that reflects the audio quality of the output signal, as depicted in Fig. 1. This comparison focuses entirely on perceptual differences, while imperceptible distortions are neglected.

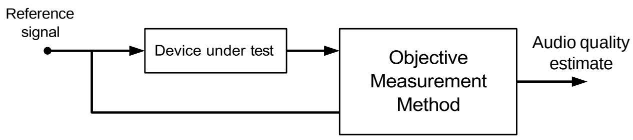

Fig. 1. The block diagram of the basic PEAQ algorithm.

II. State of the Art

Although VLC is primarily intended for broadband access, some applications use an audio message signal modulated in light intensity in the short-range VLC scenario. Evaluation of audio quality transferred via VLC is important for assessing performance, ensuring user satisfaction, optimizing system design, establishing standards, and ensuring regulatory compliance. These can contribute to the advancement and widespread adoption of the VLC technology in various audio communication applications, such as air traffic control systems, cabin crew communication systems, the music industry, to name a few. However, to the best of our knowledge, no previous research has thoroughly examined the quality of the audio signal transferred via VLC.

State-of-the-art research studies in audio transferred over VLC are primarily focused on communication in aircraft cockpits [2] and underwater voice communication systems [3]. Recently, the assessment of perceptual speech quality in VLC transmission has been explored using the perceptual evaluation of speech quality (PESQ) and the Virtual speech quality objective listener (ViSQOL) metrics [4]. In [5], a portable device for optical wireless transmission of audio signals in a VLC-based underwater voice communication system is presented. The transmitter includes a signal processing circuit, transmitter driver circuit, light emitting diode (LED), and optical antenna. The receiver contains a photodiode, photoelectric conversion, and amplification circuit. To send location information to aid the visually impaired, authors in [6] have implemented audio multicasting using VLC. The study has been executed using LEDs, which can transmit fast light pulses. The implemented system can function in both dark and bright lighting environments.

This study examines the quality of audio signal in an IM/DD (intensity modulation with direct detection) short-range analog VLC link. The impact of open hardware and open software platforms for research and experimentation has gained momentum in recent years. OpenVLC represents an open-source, flexible, and low-cost communication system platform for embedded VL networking. In our case, OpenVLC1.3 RevA capes are utilized to evaluate the quality of audio signals in IM/DD VLC indoor communication [7].

The circuit diagrams of the transmitter and the receiver are depicted in Fig. 2.

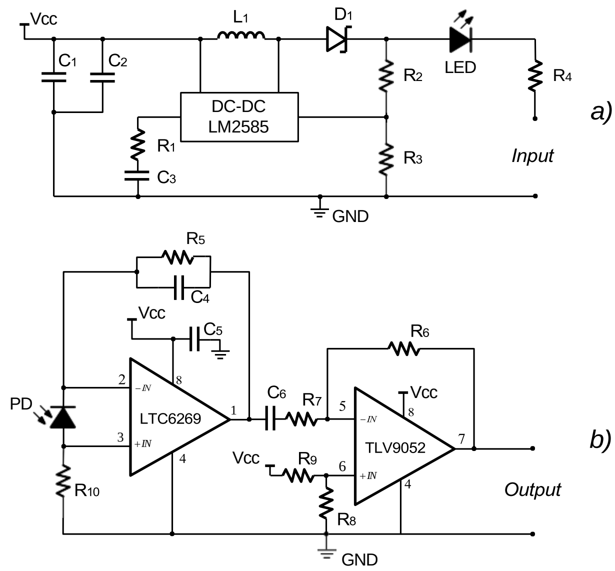

Fig. 2. The circuit diagrams of: (a) the transmitter, and (b) the receiver.

The transmitter comprises a voltage regulator and a high-power LED (high-density in warm white illumination). To ensure the proper polarization of the LED, the input signal is biased by a DC offset voltage. On the other hand, the receiver consists of a photodiode, a trans-impedance amplifier, and an amplifier. Since the photodiode generates a current directly proportional to the light intensity, the trans-impedance amplifier serves as a converter, transforming the current into a voltage signal. Additionally, an auxiliary amplifier provides additional amplification of 20 dB. The specific values of the used components are provided in Table 1.

Table 1 – The values and names of utilized components.

Transmitter		Receiver	
Item	Name/Value	Item	Name/Value
C_1	100 µF	PD	QSD2030
C_2	0.1 µF	C_4	0.5 pF
C_3	0.33 µF	C_5	0.1 µF
R_1	3 kΩ	C_6	0.1 µF
R_2	12 kΩ	R_5	75 kΩ
R_3	1.5 kΩ	R_6	100 kΩ
R_4	13.6 kΩ	R_7	10 kΩ
L_1	33 µH	R_8	150 Ω
D_1	SK310AR3GCT	R_9	150 Ω
LED	XHP35A	R_{10}	1 kΩ

The experimental testbed is shown in Fig. 3, consisting of the transmitter, the receiver, the voltage source, and the audio analyzer.

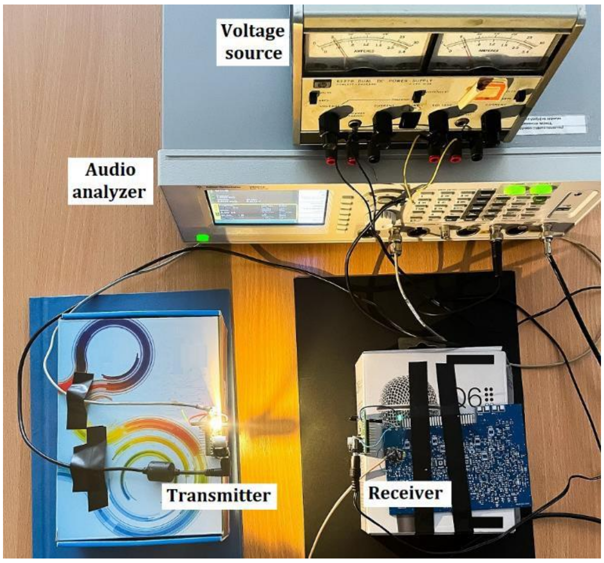

Fig. 3. The experimental testbed.

The advantages of an exploited transceiver are simplicity and non-coherent transmission. The obtained results suggest that the transmission of audio signals with faithful quality (the THD level below 1%) can be accomplished using VLC technology.

III. Challenges and Future Works

The domain of speech and audio signal processing experiences a growing interest with a broad range of specific and interdisciplinary research and development. In many modern audio and multimedia networks and devices, it is required to ensure a precise and reliable assessment of the quality of broadband audio signals. Today, when audio streaming services are among the significant consumers of internet capacity, it is of great importance to deliver high-quality audio signals. To assess the quality of the delivered audio signal, subjective but also objective methods of quality assessment are used, which model the psychoacoustic characteristics of the human auditory system.

In this paper, we provided an evaluation of the quality of the audio signal transmitted by the VLC link. Objective methods such as PEAQ, PESQ, and ViSQOL, as well as the common objective parameters of THD, SMPTE IMD, SNR, and SINAD, were considered. The currently implemented system has scopes to be developed further. The transmission range of this system can be increased while maintaining the audio quality.

Future research may include consideration of other modulation and coding techniques, as well as different modeling of the simulated VLC systems. Alternative modulation/detection schemes can be exploited, possibly combined with channel coding techniques (forward error correction). On the other hand, in the existing experimental real environment, an objective PEAQ method can be considered to assess the quality of an audio signal transmitted via an analog IM/DD VLC link. Potential future research may include examining the performance of digital audio VLC transmission. Digital communication systems provide a more faithful quality of signal regeneration after the transmission process. Common encoding strategies to convert analog audio signals into digital ones include pulse width modulation and delta modulation. Furthermore, the study will also explore the impact of the communication distance and the PD field of view on the reconstructed sound signal quality.

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Physics-based modelling of LEDs and phosphors paves the way to boost VLC performance

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I. Introduction

Radio communication has seen tremendous advance-ments through theoretical optimizations and the use of models that often surpassed the technological capabilities of their era. Notably, Shannon's theory emerged shortly after World War II, a time when ON-OFF keying and Morse code were prevalent. Presently, there's swift progress in Intensity Modulated Optical Wireless Communication (OWC), with Visible Light Communication (VLC) leveraging the ubiquitous deployment of LED lamps. Despite this, we see that the foundational communication principles from radio technologies are being repurposed for OWC. This white paper argues for the desirability, possibly even the necessity of refining theoretical foundations specifically for OWC, and VLC in particular, positing that such advancements could lead to significant improvements, especially in the context of modeling power LEDs for data communication.

In fact, many models have been proposed over the years, to describe the behavior and the light output of the LED. In information theory, the LED was long seem as the prime example of a peak (rather than power) limited channel, for which the usual Shannon capacity expressions do not hold. Also, the Gaussian distribution of a signal is not capacity achieving for non-negative signals. In fact, early LEDs were mostly driven near their maximum rated power levels, and long peaks (occurring in slow modulation) could overheat early LEDs. Today, power LEDs are operated near their most efficient operation point which is far below where irreversible damage may occur. Peaks signals of several times the average would experience droop, but such efficiency loss but not harm the LED. This would not be the case, particularly in OFDM systems where peak durations are only a matter of microseconds.

LEDs are non-linear and low pass. And it is this combination, often called *dynamic non-linearity*, that requires special attention. The capacity of a linear first-order AWGN low-pass channel, like an LED with a dynamic resistance and capacitance is known [1]. Also the capacity of a non-negative (and possibly peak-limited channel) had been studied extensively. But, to our knowledge, the capacity of a combination of a non-negative, low-pass and distorting channel has been expressed in tractable formulas. We neither know practical modulation schemes that reach (near-) capacity. In practical approaches to VLC systems, the need to mitigate the effect of the low-pass channel seems to prevail, such that subcarrier modulation methods are popular. Nonetheless, we see great improvement opportunities if the non-linearities can be addressed, particularly because multi-carrier modulation is notoriously sensitive to this.

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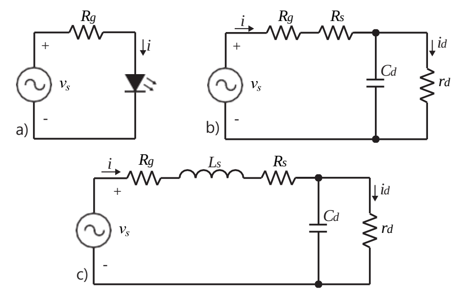

Fig. 1. LED Electrical Models: a) Target circuit; b) Basic (1^{st}-order) model; c) Advanced (2nd-order) model.

II. State of the art

For (linear) small-signal modulation, a commonly accepted equivalent electronic circuit is in Fig. 1b. Resistance r_d reflects electrical power conversion into modulated light. It is mostly modelled as the dynamic resistance, according to the Shockley equation, with typical values in the order of one Ohm. The LED junction stores electrons and holes, thus also acts as a capacitance [2]. The capacitance results in a low-pass behavior of the LED, which depends on the current [2] thus causes non-linearities [3]. Furthermore, the LED wiring introduces an inductance (Fig. 1c), adding another layer of complexity to the model [4]. These insights underscore the importance of accounting for both capacitance and inductance for a more accurate and comprehensive understanding of LED behavior in small-signal modulation applications. Following the discussion on the electronic characteristics of LEDs and their implications for small-signal modulation, for VLC it is pertinent also to address the role of phosphor in the generation of white light. White light can be achieved either through the use of RGB LEDs or by combining blue LEDs with a phosphor layer. The latter approach is generally preferred in practical applications due to its cost-effectiveness.

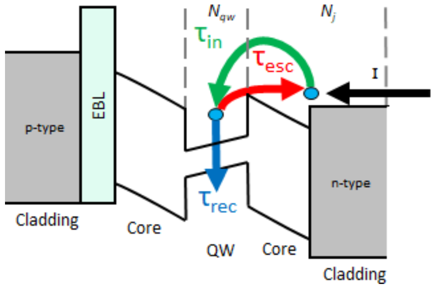

Fig. 2. Electron-hole recombination in an LED.

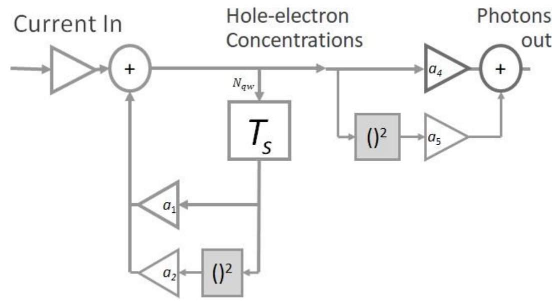

Fig. 3. Equivalent signal processing model for the quantum well [3].

Phosphor-based LEDs operate on the principle of converting blue photons emitted by the LED into white light. This conversion is facilitated by the phosphor layer, which absorbs some of the blue light and re-emits photons at longer wavelengths, resulting in a white composite light to the human eye. This process of recombination, from blue to yellow photons, is not instantaneous and introduces a time delay in the conversion, manifesting as a dynamic response. This response can be characterized as a first-order low-pass behavior, significantly influencing the modulation capabilities of phosphor-based LEDs. The inherent delay in the phosphor response to changes in the input signal is a critical factor to consider when designing and implementing VLC systems. Illumination LED manufacturers use economic considerations to reduce the amount of phosphor by driving the phosphor into saturation. As a substantial portion of phosphor is in an excited state, non-linearities may occur in modulation signals.

A. Non-linear Models

In RF communication, the antennas and the medium are linear, but in VLC, the electrical-optical (LEDs, phosphors) and optical-electrical conversions are non-linear and limited in bandwidth. For the performance of a communication link, whether or not non-linearities are invertible is highly relevant. The LED has often been modeled as a clipping device, thus with non-linearities that cannot be inverted. However, the existence of a peak value above which the light level would be clipped does not seem to reflect the properties of modern LEDs: at high current levels, the efficiency drops, but a hard clipping or thermal breakdown is not likely.

In recent years, the dynamic photonic response of the LED has been studied in detail, e.g. [3], giving the insight that LED non-linearities can not only be mitigated but can even be inverted, e.g., [5]. In fact, when using large constellations, say above 256 QAM over strong links, clipping must be kept low, but then second-order effects in photon generation become a dominant limitation. Papers such as [5], [6], [7] dive into the dynamic non-linearities of LEDs within VLC systems. These show that through modeling and analysis of these non-linearities, system performance can be enhanced substantially. Significant reductions in power consumption—up to 70%—but also the potential to enhance system throughput by 50% seem within reach [5].

The non-linearity of phosphor in LEDs, especially under high excitation levels, critically influences the modulation capabilities and efficiency of VLC systems. Ref. [8] delves into this by analyzing how phosphor saturation—driven by mechanisms like ground-state depletion, thermal quenching, and ionization—impacts light output. All in all, we see great potential in improving VLC systems, by going beyond the straight reuse of principles known from radio technology, but by exploring the dynamic response of LEDs and other photonic components and by using these in targeted physics-based signal processing approaches.

III. Challenges and Future Works

First and foremost, via this white paper, we like to encourage work that further develops a theoretical understanding of the non-linear dynamics of the LED response. Communication and information theory experts typically pitch that to effectively communicate, one must truly understand "the channel". In short-range VLC, the propagation medium (indoor air) is almost ideal, but the photonic devices (in particular LEDs and phosphors) pose severe limitations. That justifies a view on VLC as a challenge of using "the LED as a communication channel": that is, a communication link that is predominantly limited by its components. Driven by prior experience reported in various papers, the authors see further opportunities to enhance VLC performance.

Breakthroughs in innovation may not only come from demonstrating a higher throughput than previously documented systems. In fact, mass-market adoption requires that solutions work anytime, anywhere, under any circumstances. This requires verification, including extensive simulation and theoretical evaluation using generally accepted reference models confirmed by multiple research teams, similar to those widely used in radio communications, but redone for VLC focusing on limitations of components. In contrast to this practice in RF, we see in optical wireless often focus on one-time proof of concepts that show record throughput in the lab, while simulation of distrusted. This cultural difference may hamper a path to widespread mass-market applications. Besides creating trust in reproducibility and scalability, we expect significant benefits in terms of performance and power consumption from further development and verification of models for the electrical and optical behaviour of components such as LEDs and photodiodes.

A deeper understanding also paves the way for effective countermeasures. In particular, we encourage

- Development of better non-linear equalizers, in particular solutions that can work if other system components also introduce impairments.
- Studies into differences between various types of LEDs, for instance with or without relying on a quantum well.
- Modeling of the effects of phosphors.
- Modulation methods, as well as bit and power loading, can be optimized for the LED characteristics
- MIMO methods for nonlinear low-pass channels
- Development of Physical Layer standards that are better suited for optical wireless communication, including the mitigation of LED artefacts

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Current Status and Possible Directions to Gain Momentum in the Massive Adoption of OWC

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I. Introduction

The growing demand of wireless connectivity is changing the design paradigm of mobile networks. So far, the small cell densification and the re-framing of new Radio Frequency (RF) bands have been enough to reach the key performance metrics that have been set for the new 5G kinds of services. However, if the demand for mobile data traffic continues to grow as in the past decade, it is a matter of fact that RF technologies alone will not be enough to face the *"data tsunami"* that the new use cases Beyond 5G (B5G) will require. Therefore, novel wireless communication technologies using optical frequency bands will be needed to provide connectivity in the scenarios in which the use of RF-only is either not possible or practical. The foundational notion of utilizing light waves for the transfer of information can be traced back to the 1880s, when Alexander Graham Bell successfully showed the transmission and reception of voice signals using his *"photophone"* apparatus, spanning distances of few hundred meters. However, the development of modern Optical Wireless Communication (OWC) systems started much later, in the 1960s, thanks to the invention of the Laser Diode (LD) that enabled a larger communication bandwidth and better coverage than previous systems that used light bulbs. Unfortunately, most of the OWC experiments performed in this period of time gave disappointed results, mainly due to hardware limitations in the LD technology that existed in those days. Moreover, with the development of low-loss optical fibres in the 1970s, the commercial development of optical communications was steered into the direction of fibre links. The use of OWC was mainly restricted to military and space applications. The only exception is perhaps the Infrared Data Association (IrDA) standard, which became a popular solution for short-range OWC links in the 1990s [2]. Nevertheless, with the introduction of white Light Emitting Diodes (LEDs) for indoor illumination, the development of OWC technologies gained momentum again with focus on the provision of optical wireless access in indoor scenarios.

The challenges of implementing OWC systems in practice have many similarities to the ones faced in other kinds communication systems in the past decades (see Fig. 1). For example, as in radio wireless communications, OWC systems rely on electromagnetic signals that propagate though an unguided medium which is know as the *"air"* or the

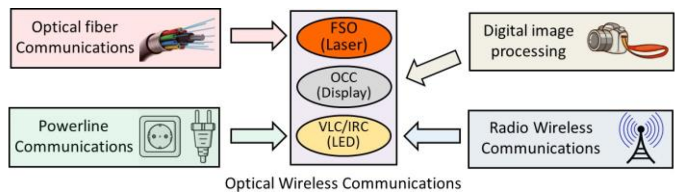

Fig. 1. Areas of communications engineering that are influencing the develop-ment of Optical Wireless Communications (OWC) technology. Terminology: Free Space Optical (FSO), Optical Camera Communications (OCC), Visible Light Communications (VLC), and Infrared Communications (IRC).

"free space". However, the light sources (LEDs or LDs) and detectors (Photodiodes) that are used in OWC transmitters (Tx) and receivers (Rx), respectively, are much more similar to the ones used in optical fiber communications. Moreover, the low-pass response of the OWC channel, including the time response of the LED and the Photodiode, resembles much more the one observed in a Powerline Communication (PLC) system rather than the frequency selective response of a radio communications system. Finally, when a digital camera is used as RX in an Optical Camera Communication (OCC) system, the challenges to be faced have notable overlapping with the ones existing in digital image processing. This is the reason why multi-disciplinary approaches are needed to tackle the key challenges to facilitate the adoption of OWC technology.

OWC systems aim at supporting high data rates while providing high levels of physical-layer security. To pave the way for its massive adoption, OWC systems should use low-cost off-the-shelf components such as commercial LEDs (or LDs) and photodiodes. In the transmitter side, the data-carrying signal takes the form of an electrical current that drives the intensity of the LED (or LD), which is in charge of the electrical-to-optical conversion. Data rates in the order of few (tens of) gigabit-per-second (Gbps) have been experimentally demonstrated using LEDs (or LDs) as light sources. Although LEDs present a narrower electrical modulation bandwidth (i.e., slower time response) and less directional light beam transmissions when compared to LDs, their simplicity, eye-safety properties, and low cost make them a popular choice for indoor wireless access through small cell deployments. In addition, when using phosphor-converted and/or tricolor (RGB) LED technologies, the same aggregated white light that

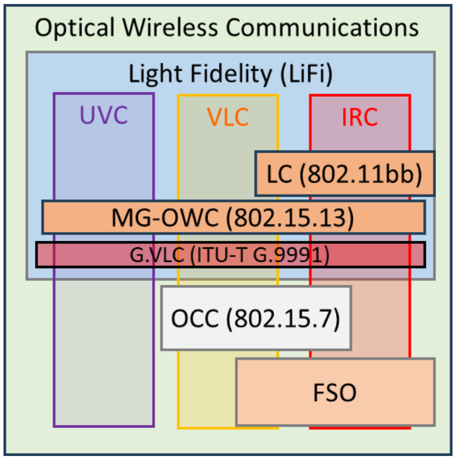

Fig. 2. Summary of the terminology used by the academic and the industrial sector to classify the different kinds of OWC systems that can be implemented. The relation that exists between each of these terms are also visualized.

the OWC emits for communications can be re-used for the provision of illumination. In contrast, LD are more suitable for long-range directive point-to-point connectivity mainly outdoors, which fits very well for the provision of terrestrial (building-to-building), ground-to-air (airplanes), ground-to-space (satellites) and inter-satellite point-to-point links.

II. State of the Art

This section starts with a brief discussion on the OWC terminology used in the literature for more than a decade. After that, a summary of the standardization efforts on OWC technology are briefly presented, summarizing the kinds of stakeholders that have been actively involved in each of them.

A. OWC Terminology

Over the recent years, the research community has developed advanced OWC-based concepts for various applications. In particular, the last decade has observed notable growth of optical wireless systems by the introduction of the Light-Fidelity (LiFi) network concept and due to both technological advances and an increase in potential use cases. In this regard, various terms have been used for relevant technologies, which are not always correctly used in some cases. Therefore, the aim of this section it to reflect on the most appropriate terminology that should be used when discussing each of these OWC-related cases. Fig. 2 illustrates the landscape of terminologies, pinpointing potential differences and overlapping among them. Subsequently, each term is defined below:

• *Optical Wireless Communication (OWC)* stands as the broadest term, encompassing any wireless communication system leveraging segments of the electromagnetic spectrum referred to as "light," including ultraviolet, visible, and infrared bands.

• *Light Fidelity (LiFi)*, introduced in 2011, emphasizes the utilization of optical wireless technologies for indoor bidirectional multiuser network access. Typically, a blend of visible (mainly downlink) and infrared (uplink and downlink) spectra is employed. LiFi can be conceptualized as the optical counterpart to radio Wireless Local Area Network (WLAN).

• *Free Space Optical (FSO)* communication pertains to high-speed point-to-point wireless links, predominantly for outdoor applications. Long ranges and high data rate requirements necessitate the use of LDs as the primary light of source in the transmitter, thereby enabling the accommodation of both Intensity Modulation/Direct Detection (IM/DD) and coherent communications methodologies.

• *Visible Light Communications (VLC)* involve mainly one-way (downlink) wireless links utilizing visible light LEDs (i.e., single-color, multi-color, phosphor-converted) as the primary source of light in the transmitter device. Consequently, joint illumination and communication (e.g., broadcasting) represent the typical applications for VLC.

• *Optical Camera Communications (OCC)* diverge from a conventional (single-/few-element) photodetector-based systems by the use of digital cameras as sensor in the receiving devices. Due to the relatively low sampling rates (or equivalently, detection bandwidth) in digital cameras, OCC is regarded as a low data rate communication system adding a second functionality to cameras (e.g., mobile phone cameras). In some cases, LED displays and digital screens are used as the transmitted device contributing to low-cost OCC deployments.

• Other terms include *Ultra-Violet Communications (UVC)* and *Infrared Communications (IRC)*, which only aim to refer to the optical portion of the spectrum that is being utilized. It is noted that these terms are less popular in the OWC research community than the ones listed above. There are also few specific term exclusively used in standards, namely, *Light Communication (LC), Multi-Gigabit Optical Wireless Communication (MG-OWC),* and *G.VLC*. We will discuss this OWC standard-related terminology in the next sub-section.

B. OWC Standardization

One of the advantages of OWC is the utilisation of license-free electromagnetic spectrum. However, communication technology standards are still required for massive adoption and interoperability of technologies developed by various counterparts. The following are three major standardisation efforts, for which the details can be found in the relevant documentations:

• *IEEE 802.11bb* [4] is the latest LiFi standard which utilises the light spectrum in the 800 − 1000 nm band. IEEE 802.11bb uses the term *Light Communication (LC)* to refer at its OWC system that achieves a bidirectional communication with data rate transmissions ranging from 10 Mbps to 9.6 Gbps. Importantly, 802.11bb is based on the current WiFi standards (e.g., 802.11ax) in order to reduce the implementation complexity and enable the utilisation of existing WiFi chips. For example, Wi-Fi authentication and encryption, as well as up conversion and down conversion of RF carrier frequencies, are among the adopted features in IEEE 802.11bb.

• *IEEE 802.15.13* [5] is developed by the IEEE 802 standards committee on Wireless Specialty Networks (WSN) standards. IEEE 802.15.13 is the successor of the 802.15.7 standard which was first introduced in 2011. The term MG-OWC is used in this standard to support data rates as high as 10 Gbps. Being based on RF communication, Multiple-Input Multiple-Output (MIMO) as well as low-latency access can be realised.

- *ITU-T G.9991* [6] is a sub-standard within the G.hn family of ITU-T standards aimded for home networking. The technology is referred to as G.VLC. It uses Direct Current-biased Optical (DCO-) and Asymmetrically Clipped Optical (ACO-) Orthogonal Frequency Division Multiplexing (OFDM) in the physical layer with data rates up to 2 Gbps, which is supported by a MaxLinear baseband processor chipset. The existance of a compatible silicon solution has been the main driver for rapid implementation of LiFi systems based on this standard.

C. Stakeholders involved in OWC technology development

While there has been a significant progress in the work done by the academic research community, the OWC industry landscape has been challenging but at the same time promising. The are a few companies who manufacture LiFi products, including but not limited to, pureLiFi, Oledcomm, Signify, and Fraunhofer Heinrich Hertz Institute (HHI). Commercial products rely on two of the previously listed standards: pureLiFi products use IEEE 802.11bb and the others mainly use ITU-T G.9991. In fact, these OWC equipment manufacturers have partners from automotive, space, healthcare, and defence sector for developing a number of solutions. The interest from the defence sector has gained momentum recently, owing to the fact that the physical properties of light propagation enhance the security and reduce the possibility of remote detection (jamming) by a potential eavesdropper (attacker).

There has also been strong efforts to design chipsets specially tuned for LiFi network equipment and terminals. However, due to the lack of a massive market demanding these LiFi chips today (e.g., manufacturers of smart devices such as smart phones or tablets), all these efforts have not led yet to a LiFi-specific chipset. Furthermore, the immense investment that different stakeholders in the telecommunications market have made into 5G and WiFi 6/7 systems is also a strong barrier for new investments into OWC technologies. Indeed, some of the mobile/wireless service providers and operators are interested in OWC technologies and are following (and in some cases also guiding) its development closely. It is evident that the route towards a massive market pass either through the inclusion of OWC technologies in user equipment (e.g., smartphones, tablets and laptops), or through integration of OWC technologies into future networks by standard development organisations such as 3rd Generation Partnership Project (3GPP). In line with this, the Light Communication Alliance (LCA) has been established by some of the industry and academia leaders in the field of OWC with a mission to bridge the gaps, particularly in the current stakeholder ecosystem. LCA can play a pivotal role in fostering collaboration and effective knowledge exchange between all the involved stakeholders.

III. Challenges and future works

The evolution of the adoption of OWC technology from niche markets to massive market is a challenging procedure marked by technological innovation, market demand, and strategic alignment of industry stakeholders (see Fig. 3). This section outlines the steps that would be required for to transition of OWC technology from specialized niche applications to a widespread use in massive domestic markets.

The path to mass market adoption seems to be hindered by a *not-so-clear* matching between problem and solution. The critical question arises: *Who brings the arguments forward?* and *who should invest the money?* Stakeholders, including technology developers, chipset and hardware manufacturers, and early adopters, should collaboratively articulate the massive adoption of OWC. Demonstrating tangible benefits, such as the capacity for high-density deployment without spectrum saturation, becomes imperative. Moreover, investment in OWC should be viewed as a strategic move to future-proof connectivity infrastructure, appealing to both private and public entities interested in leveraging next-generation mobile (5G/NR and beyond) and wireless (WiFi) technology.

A significant challenge in the adoption of OWC is the initial skepticism from user equipment manufacturers, who would solely be interested in the incorporation of OWC interfaces to their terminals to enable new services that cannot be offered today over RF and, at the same time, can reach large-enough demand from their customers to justify the investment. This challenge necessitates a dual approach: a) Identifying killer applications in domestic markets that clearly demonstrate the unique advantages of OWC over existing RF-based technologies; b) Addressing the economic and practical concerns of scalability and market viability of telecommunications service providers. To identify killer applications for OWC, their cost-effectiveness, openness, and ease of installation need to be conisdered, which contrast with the complexity and limitations of current RF-based wireless technologies (e.g., WiFi 6/7, 5G private networks, etc.), or fiber optic solutions to the individual rooms. For instance, the deployment of OWC can significantly reduce the infrastructure and maintenance costs associated with wired networks, while offering comparable performance.

While the existence of OWC standards is crucial for the interoperability among equipment produced by different manufacturers and for ensuring a performance baseline, they are not sufficient alone to guarantee the adoption of the technology by the mass domestic market. For this, OWC technology must be embraced by a critical mass of manufacturers, service providers, and end-users, as shown in Fig. 3. This necessitates a concerted effort to not only develop and promote standards, but also to build a robust ecosystem around OWC. Such an ecosystem would include device manufacturers, application developers, and content providers, all working together to create a compelling market offering.

To this direction, the widespread acceptance of OWC for the provision of wireless access in indoor environments, combining both visible light and infrared bands, presents an ideal starting point due to their inherent demand for high-speed, low-latency, and secured data transmission. The advantages of OWC in such settings lies in their ability to offer increased

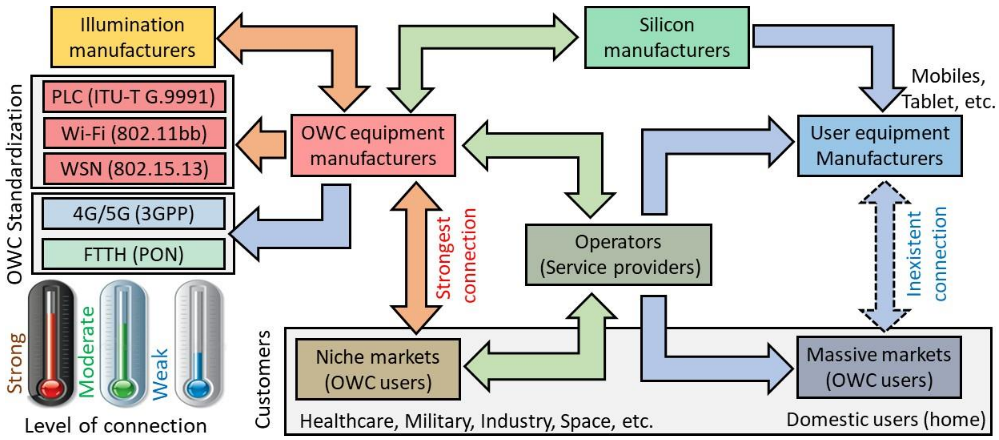

Fig. 3. Stakeholders and existing/under-development connections that are needed to pave the way to the massive adoption of OWC technology in domestic markets. Color of arrows show the presence of strong (red), moderate (green) and weak (blue) interest. Arrow directions show the interest of stakeholders.

reliability, high capacity, and increased connectivity, mainly due to avoidance of electromagnetic interference challenges associated with RF-based systems. Managing to increase the quality of experience by using OWC in indoor environments is an important milestone, since network traffic that originates from indoors under normal conditions already exceeds 80% of the total demand [7]. Also, it deserves to be noted that the potential of OWC extends beyond mere data transmission, since they can be integrated with all optical networks, providing seamless connectivity across various platforms. Additionally, the use of light for communications and illumination opens up innovative applications in smart lighting and indoor sensing systems, giving further incentives towards OWC adoption.

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Quantum Communications over Free Space Optical Satellite Links: Challenges and Opportunities

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I. Introduction

Quantum Key Distribution (QKD) enables the generation of secret keys between two legitimate parties in a point-to-point manner by encoding the information into *quantum states*. QKD is fundamentally different from conventional key exchange methods in which security relies on the computational complexity of solving a discrete logarithm problem. In contrast, it is based on physical processes that are not in principle vulnerable to powerful computers. QKD can be also classified as an optical technology for the delivery of encryption keys between two parties connected with an optical link that can be wired, through optical fibers, or wireless, via Free Space Optical (FSO) links. Unfortunately, QKD networks based on optical fibers face serious problems when trying to distribute secret keys on wide geographical areas. This is because the power loss that the optical fiber introduces grows exponentially with distance, limiting the rate at which secret keys can be successfully generated over far-away geographical points.

The intrinsic *distance-limited* point-to-point nature of a quantum link is a bottleneck for its applicability on a global scale. Fortunately, the coverage range of a QKD system over FSO links can be extended by using trusted relays, untrusted relays, or quantum repeaters [1] that can be placed onboard satellite payloads to make them difficult to eavesdrop and/or tamper. Apart from providing improved security thanks to the use of extremely narrow laser beams, FSO satellite links experience less attenuation than terrestrial optical fiber links as most of the absorption losses, which are added on top of the quadratic free-space propagation loss, are concentrated in the low-layers of the atmosphere. Different satellites can be used for this purpose, such as Geostationary (GEO), Medium Earth Orbit (MEO), and Low Earth Orbit (LEO) satellites.

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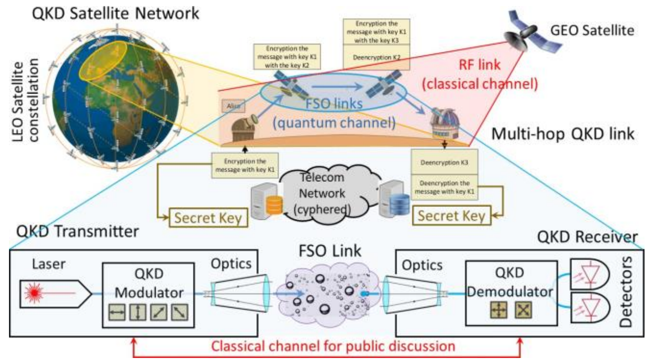

Fig. 1. Overview of a quantum communication system relying on ground-to-space and inter-satellite FSO links to generate quantum-secure keys. Classical (red) and quantum (blue) channels are used to implement the QKD protocol for secure key generation among legitimate/trusted users on ground.

The use of GEO to implement a QKD network can provide a slow but continuous secret key generation rate thanks to its fixed position on the sky at a very high altitude (about 36 000 km). QKD networks based on LEOs, which are much closer to the Earth's surface (about 1 000 km), can provide a faster key generation rate. However, since LEOs are visible for about 10 minutes when flying over a given position on Earth, the QKD service will not be continuous unless a LEO constellation is used. Finally, MEO satellites provide a tradeoff solution between GEO and LEO in terms of quantum key generation rates. Although the QKD service remains intermittent when relying on MEOs, its availability is extended to a few hours thanks to its higher orbit altitude (about 20 000 km). Fig. 1 illustrates how ground-to-space and inter-satellite FSO links can be combined to implement a QKD network with global coverage. The point-to-point inter-satellite QKD link that is illustrated in this example consists of a quantum channel (single-headed blue arrow between LEO satellites) and a classical channel (double-headed red arrow between QKD transmitter and receiver). The quantum channel is used for transmitting the quantum states (e.g., single-photon polariza- tion) of the QKD protocol. The classical channel is used to exchange classical information for synchronization and secret key distillation between both legitimate parties. The symmetric quantum-secret key generated between both legitimate parties (i.e., Alice and Bob) is then used by a symmetric cryptosystem for message encryption (grey cloud in the center of the figure).

II. State of the Art

Fig. 2 shows the layered approach of a QKD network (L3: green layer) that relies on (un)trusted relays and/or quantum repeaters to extend the range at which the secret keys can be generated. Each hop of this *mesh* network implements a quantum protocol (L2: purple layer) that relies on a QKD

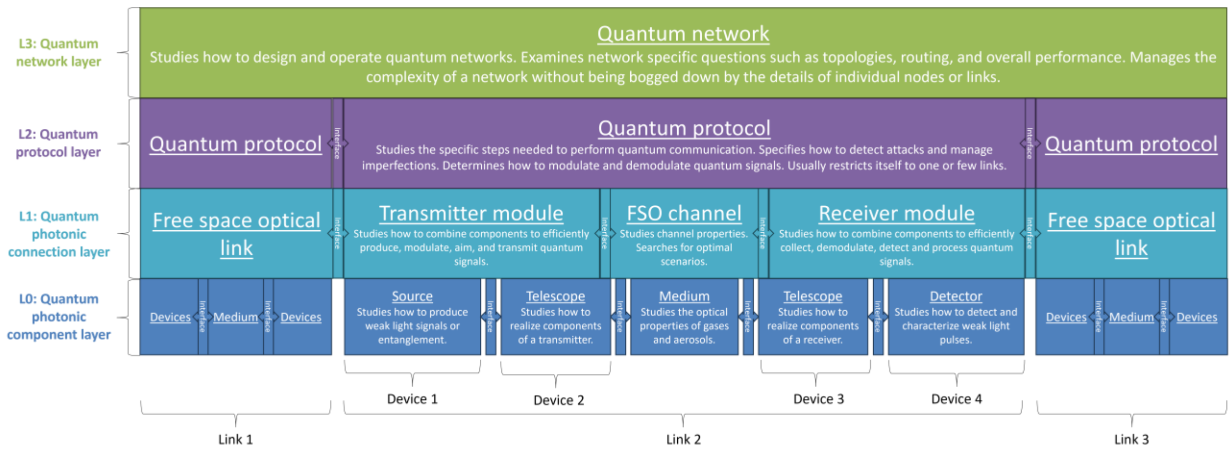

Fig. 2. Layered approach used to discuss the different disciplines that are involved in the development of a quantum communication (QKD) network.

transmitter and receiver interconnected with an FSO link (L1: cyan blocks) that convey the quantum states between legitimate users. Finally, the lowest layer (L0: blue blocks) contains the QKD components of the FSO quantum links.

A. Quantum network layer

Most of the research that discusses the implementation of a QKD network in a global scale considers the use of LEO satellites as (un)trusted relays or quantum repeaters, taking advantage of the low path loss that is introduced [2]. However, since a quantum LEO satellite is only visible to a particular ground station for few minutes, its secret key generation rate is only available during the flyover time few times a day. When trying to provide a continuous QKD service in this situation, the use of a LEO constellation with inter-satellite FSO links can be considered as a solution to enable continuous service (see Fig. 1). However, in most of these cases, the allocation of resources among ground-to-space and inter-satellites links should be optimized accordingly in order to maximize the performance of the whole (global) QKD network [3].

Constellations of quantum satellites can extend the service range of a QKD system from a single point-to-point link to a wide area QKD mesh network with global coverage. Enhancing the range and secret key generation rate of such QKD system can be achieved through the substitution of the potentially lengthy point-to-point quantum links with a series of shorter quantum links interconnected through intermediary nodes. Such configuration would minimize the power loss in each of the shorter point-to-point quantum links, resulting in a higher amount of secret keys generated in the whole QKD system. A constellation of LEO satellites is the ideal option to enable the forwarding of quantum keys from legitimate users via FSO inter-satellite links. Then, the combination of routing protocols with multi-hop QKD links comprise a quantum communication network [1] that should optimize the use of its resources (e.g., secret keys generated in the intermediate nodes) to maximize the overall QKD network performance [3].

B. Quantum protocol layer

The no-cloning theorem is one of the laws of quantum mechanics used in QKD, which states that it is not possible to create identical copies of a quantum state. Then, if a hypothetical attacker (i.e., Eve) listens to the communication (i.e., measures the quantum states), the system would change in such a way that Alice and Bob will notice it.

TABLE I

List of most popular QKD Protocols [4]

Name	Authors	Year	Type	Principle
BB84	C H Bennett, G Brassard	1984	DV	HUP
E91	A Ekert	1991	DV	QE
B92	C H Bennett	1992	DV	HUP
Silberhorn	C Silberhorn	2001	CV	QE
DPS	K Inoue, E Waks et al.	2002	DV	QE
GG02	F Grosshans, P Grangier	2002	CV	HUP
Decoy-state	HK Lo, XF Ma, K Chen	2003	DV	HUP
SARG04	V Scarani, A Acin et al.	2004	DV	HUP
COW	D Stucki, N Brunner et al.	2005	DV	QE

Abbreviations: CV = Continuous Variable; DV = Discrete Variable; HUP = Heisenberg's Uncertainty Principle; QE: Quantum Entanglement.

Table I shows the list of the most popular QKD protocols, which can be broadly divided into two categories of QKD systems: Discrete variable (DV) and continuous variable (CV).

1) *DV-QKD:* Single photons are sent through the quantum channel, one at a time, and the information is usually encoded in the polarization state or time-bin/phase of each photon. Single-photon detectors are used here. DV-QKD systems can generate secret keys at relatively low rates [5][6][7]. DV-QKD systems are generally more tolerant to strong path loss attenuation and, due to that, best suited for long-haul networks.

2) *CV-QKD:* A coherent state of light is sent, as in most classical optical communication systems. The beam gets attenuated such that the wave packets contain less than one photon on average. Optical components based on mature technologies are utilized here. At short distances, relatively high secret key rates can be obtained with CV-QKD systems [5][6][7]. For this, the information can be encoded by modulating the amplitude and phase of the electromagnetic wave that is emitted by the light source. CV-QKD provides the best performance in metropolitan networks as they are less tolerant to strong losses. CV-QKD also has some issues with its security proofs not being as advanced as the ones in DV-QKD counterparts.

C. Quantum photonic connection layer

This layer deals with the design of the transmitter and receiver modules of the quantum channel, aiming at fulfilling the characteristics of the FSO satellite link through which the communication will take place. Here, the qubits are mapped onto physical entities, such as the polarization state of single photons. The physical implementations of the abstract entities used in the higher layers often do not behave exactly as expected due to technical limitations. For example, actual single-photon sources generate multi-photon states with probabilities that can be known *a priori*; thus, the design of the QKD protocol must take into account these imperfections that are associated to the physical devices (hardware) that is used.

The behavior of the transmitter and receiver devices can be modeled at different levels. For example, the so-called *density matrices* can describe statistical mixtures of quantum states. Then, with the aid of this information, the reliability of the photon source can be characterized. Similarly, the photon generation rate gives information about the efficiency of the source. Regarding the mechanical and electric parts of the device, orbit and attitude control systems must be used in the case of satellite-borne devices for QKD networks. Tracking systems and optical correction (e.g., polarization state) must be performed for ground stations. The behavior of the optical wireless channel can be modeled using a superoperator that acts on the density matrices defined by the transmitter, inducing a combination of unitary transformations that can be corrected using a single unitary transformation at the receiver. In [8], [9], different models based on the use of unitary operators and superoperators for describing the nonidealities of quantum channels are proposed and tested. Qubit errors can be addressed with quantum error correction schemes.

D. *Quantum photonic component layer*

At the lowest layer of Fig. 2 we have the physical components (hardware) of the quantum communication system. Out of them, the photon sources and detectors are notably different from the ones used in classical laser-based communications.

1) Photon sources: There are several types of photon sources as different QKD protocols require different types of them. The most widely used ones are now briefly introduced:

- *Attenuated lasers* are cheap and reliable. The number of photons that they produce per pulse closely follows a Poisson distribution [10]. Attenuated lasers are excellent photon sources for CV-QKD protocols. Attenuated lasers can also be used to implement DV-QKD protocols that would require single photons (e.g., BB84 protocol), but in this case they must be supplemented with decoy states to detect photon number splitting attacks. It is also a necessary to use photon sources that emit a mean number of photons that is less than one to reduce the probability of vulnerable multi-photon states.
- *Entangled photon sources* are necessary for QKD protocols such as E91 and BBM92. Entangled photon sources are necessary QKD protocols that perform Bell-test experiments, which can serve as the basis for device independent QKD systems in which parties do not have to trust the device manufacturer. The most common way of producing entangled photons is by Spontaneous Parametric Down Conversion (SPDC). In this process, a nonlinear crystal splits the higher energy photons from a pump beam to two lower energy entangled photons.

2) Photon detectors: Single photon detectors are dominated by two major types, namely semiconductor-based Single Photon Avalanche Detectors (SPADs) and Superconducting Nanowire Single Photon Detectors (SNSPDs) [10].

- *SPADs* use a reverse biased diode that blocks the electrical current until an incoming photon generates an avalanche current [10]. SPADs are small in size, light in weight, and cheap in terms of cost. However, their performance metrics are not the best and they can be damaged by intense light.
- *SNSPDs*, on the other hand, use a superconducting nanowire that has no resistance [10]. When an incoming photon hits the detector, it disrupts superconductivity forming a detectable voltage drop. SNSPDs have very high performance but can be expensive and they require a cooling system to keep a suitable working temperature. This entails the use of heavy and bulky cryostats, restricting their use to ground stations.

TABLE II
A (NON-EXHAUSTIVE) LIST OF CHALLENGES THAT SPECIALISTS ON THE LAYERS OF A QKD NETWORK SHOULD BE CONCERNED ABOUT.

Layer	Topics	Issues
Quantum netw. layer	Multi-hop system design	Trust requirements, performance requirements, satellite constellations, ground station locations, interoperability
	Networking	Routing, optimization, end-to-end performance
Quantum protocol layer	Quantum protocols	BB84, E91, BBM92, entanglement swapping, entanglement distillation
	Related classical protocols	Authentication, reconciliation, error correction, privacy amplification, classical cryptography
	Trust guarantees	Security proofs, error estimation, device indep. QKD
Quantum photonic connection layer	Satellite design	Size, weight, power, life cycle, space qualif., redundancy
	High-level telescope design	Telescope types, mounts, optomechanics, control electronics, pointing, tracking, adaptive optics
	Link design	Link budget, optical wavelength, satellite orbits, uplink or downlink, day time or night time operation
	OGS design	Domes, building codes, local regulations, infrastructure
Quantum photonic component layer	Lasers	Photon statistics, repetition rate
	SPDC	Nonlinear optics, phase matching
	Telescope comp.	Lenses, coatings, losses, coupling effic., opt. aberrations
	Atmosph. model	Raman modes, Mie-scattering, opt. turbulence
	SPAD	Semiconductors, afterpulsing
	SNSPD	Superconductors, hotspots, latching

III. CHALLENGES AND FUTURE DIRECTIONS

To conclude this paper, some of the key technological challenges to facilitate the adoption of QKD-over-FSO are briefly presented. In addition, the opportunities that may emerge once the maturity of QKD network technologies reaches the level needed for *commercialization* are also briefly summarized. Table II presents an compilation of challenges experienced by specialists working on the different layers of a QKD network.

A. *Challenges of implementing trusted nodes and resource management in a QKD network*

The operation of quantum communication networks is hindered by challenges involving the establishment of trusted relay nodes, the design of new protocol for multi-hop QKD, and the joint allocation of resource in the QKD network:

1) Multi-hop QKD Routing: Presents a unique set of challenges in contrast to classical routing, as it operates with the primary objective of securely delivering encrypted packets containing a secret key. This plays a crucial role in encrypting messages transmitted across a classical network, as each hop necessitates both a quantum channel and a classical channel. The transmission capacity in QKD routing to a candidate *next hop* node is contingent upon both the classical channel capacity and the locally generated QKD secret key rate. Furthermore, in QKD routing, only trusted nodes are eligible as *next hop* candidates, introducing an additional optimization constraint. Consequently, QKD routing may encounter challenges stemming from a restricted pool of eligible next hop nodes, leading to an increased likelihood of path-finding failures when compared to the more permissive classical routing algorithms. Finally, since the use of each node consumes secret keys from its pool, another challenge in QKD routing is to find the minimum number of trusted nodes required to achieve the target quality of service.

2) Resource Management and Entanglement: The management of communication resources is a crucial task in classical wireless systems. Similarly, to ensure the end-to-end performance in a QKD network, power allocation, optimal relay node activation, and establishment of the joint quantum-classical link, among others, need to be optimized. Without a classical counterpart, entanglement-sharing creates novel challenges for quantum networks as, without a widespread use of quantum memories, it is very difficult to maintain the shared entangled states without decoherence phenomena. This leads to additional constraints in entanglement-based protocols that limits the allowed duration of the key distribution phase.

3) Interoperability: On top of the previously listed challenges, different operators may take part in the development of the LEO constellation and the QKD network infrastructure, leading to minor (or major) differences in the implementations on the different QKD network layers. Due to this, the QKD network needs to safeguard the interoperability through standardization, which is something *necessary* (but not *sufficient*) for the massive adoption of any new technology. Finally, the identification of suitable markets, beyond governmental, military and scientific ones, is something that must be explored.

B. Beyond point-to-point QKD Protocols

The existing QKD networks only provide point-to- point (P2P) secret key distribution services rather than point- to-multipoint (P2M) ones. However, some information applications like broadcasting need P2M key distribution. Although P2P key distribution can be used can be used for P2M services, secret keys of the intermediate nodes must be consumed during this process. Then, when the load of the QKD network increases, its performance tends to decrease. The Quantum Conference Key Distribution (QCKD) protocol [11], which allows a node to simultaneously share a conference key, has been developed to perform the P2M encryption at once. Another protocol, known as the Quantum Conference Key Agreement (QCKA) [12], is more suitable for a cryptographic task in which more than two parties wish to establish a common secret key. The efficient integration of QCKD and QCKA protocols into QKD networks is an important issue.

C. FSO channel models for quantum information transfer

The fundamental properties of the quantum communication signals render the agnostic use of existing FSO channel models problematic. On the other hand, pure quantum mechanical descriptions of the quantum signal propagation by solving, e.g., the Schro¨dinger equation for every qubit, are not practical. Therefore, new models need to be designed to bridge this *rift* between the quantum mechanical world and the FSO channel modeling. One possible way forward is by exploiting the accumulated knowledge from the FSO channel modeling research to characterize a quantum operator to model the effect atmospheric turbulence has onto a series of transmitted qubits.

D. Limitations of State-of-the-Art quantum photonic components and future technologies to increase their performance

QKD components are still under development and, so far. For example, producing true single photons is hard, and currently single photon sources are in experimental phase. Quantum dots, ion traps, artificial atoms and crystal defects are promising candidates for such a source [10]. Similarly, entangled photon sources based on SPDC produce high quality photon pairs at room temperature [10]. However, the SPDC process is inefficient, leading to low brightness. Increasing pump power improves the pair generation rate but can lead to vulnerable multi-photon states. Quantum dots, on the other hand, are new and improving entangled sources [10]. They can be bright and do not suffer from multi-photon generation at high brightness. However the quality of produced entangled photons is generally low and they require intense cooling.
In addition, the precise synchronisation of quantum communication components is crucial as it leads to an improvement in the bit rate of the quantum key distribution and increases the signal-to-noise ratio. Such a synchronisation system can make the quantum networks independent of third-party synchroni- sation systems (e.g. Global Navigation Satellite System), but requires precise compensation of the optical line taking into account accurate environmental measurements."

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Optical Technology for Joint Communication and Sensing

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I. Introduction

The current trajectory of wireless communication technology is leading us to the next milestone, the sixth generation, or 6G, of networks. Historically, wireless networks have been at the forefront of delivering robust mobile broadband and ever-increasing data rates. However, we are witnessing a transformative phase in the evolution of these networks, a phase that expands the traditional focus from pure data transmission to a multifaceted approach that includes sensing and localization capabilities [1]. These functions, previously on the fringes of network design and capability, are now taking center stage. The Internet of Things (IoT) era requires networks that not only transmit data, but also have a high level of awareness of their operating environment. Such integration aims to transform passive networks into active systems capable of interacting with and adapting to their environment in real time. It should be noted that this integration has already influenced standardization activities, including IEEE 802.11 [2]. In this context, optical wireless communication (OWC) is expected to play an important role in these advanced functionalities of future communication networks.

In particular, the integration of optical wireless (OW) and radio frequency (RF) technology in hybrid networks offers a promising solution to the challenges of current and future communication needs [3]. OWC uses light-emitting diodes (LEDs) and lasers to transmit data and can offer benefits such as reduced interference and low latency, which are critical for real-time processing and rapid data transfer. A defining characteristic of this technology is its narrow beamwidth, which can significantly improve angle-of-arrival measurements, making it ideal for applications that require pinpoint accuracy in localization efforts, such as indoor navigation systems, advanced robotic operations and augmented reality scenarios. The potential applications for OWC are thus diverse and hold great promise for several sectors. In transportation, for example, it could revolutionize the way vehicles communicate with each other and with infrastructure, improving traffic flow and safety. In industrial environments, it could enable more accurate asset tracking, better process monitoring, and predictive maintenance through real-time sensing. In healthcare, the use of this technology could lead to improved patient monitoring systems, smarter management of medical devices, and improved delivery of care services. The convergence of OW and RF systems could further enhance these applications by leveraging the strengths of each technology. RF technology, with its proven long-range and obstacle penetration capabilities, complements the high speed and precision of OWC. By taking advantage of both optical and RF technologies, hybrid networks can provide robust, reliable and highly accurate wireless communication solutions. As wireless technologies have evolved, fiber has emerged as a powerful medium for joint communication and sensing (JCS), providing a complementary solution to hybrid OW and RF systems. Fiber optic technology is known for its unparalleled ability to transmit data over long distances with high bandwidth and minimal signal degradation. Beyond communications, these fibers can serve as distributed sensors capable of detecting temperature changes, pressure fluctuations and acoustic vibrations along their length.

In the context of JCS, research efforts can be grouped into two primary themes. The first theme revolves around the development of **networks that can simultaneously support communication and sensing functions**, enabling a single piece of infrastructure to handle multiple tasks, which can lead to cost savings and increased efficiency. The second theme focuses on **environmentally aware communications**, where networks use their sensing capabilities to enhance their performance. By actively responding to environmental changes, these networks can maintain consistent quality of service even in the face of disturbances or obstacles, making them self-optimizing and resilient.

This contribution aims to provide a thorough examination of how the integration of OW technology with RF systems can enhance the sensing and localization capabilities inherent in wireless networks. We will discuss the research frontiers in the areas of simultaneous communication and sensing, as well as environment-aware communications, shedding light on the future possibilities of hybrid OW and RF technology. This integration is expected to reshape the landscape of wireless networks, transforming them from passive data channels to active entities aware of the ever-growing ecosystem.

II. State of the art

A fundamental aspect of current advances is addressing the inherent compatibility and potential conflicts between communication and sensing functions. Both domains, RF and OWC, share a confluence of advantages such as bandwidth reuse and the synergistic use of multi-input multi-output (MIMO) technologies. These shared advantages lay the groundwork for the development of systems that leverage both communication

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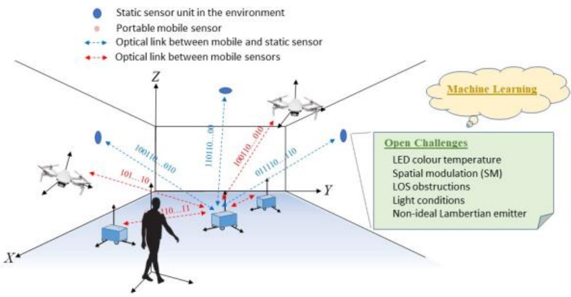

Fig. 1. Centralized optical local positioning system

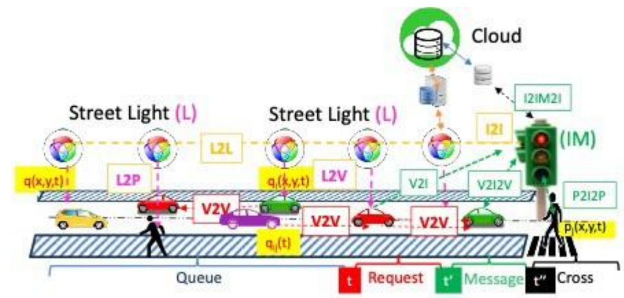

Fig. 2. OWC for adaptive traffic control

and sensing capabilities, albeit with inherent challenges related to waveform tradeoffs and sensor performance metrics.

The use of OWC, particularly through visible light communication (VLC) and infrared (IR) techniques, has led to advances in 3D sensing and localization, as shown in Fig. 1. Innovations such as spatial modulation for improved 3D indoor positioning exemplify the progress made in achieving high spectral efficiency and interference-free transmission [4]. However, these advances are not without challenges, particularly the line-of-sight (LoS) requirement and susceptibility to ambient light interference. It should also be noted that the role of spatial modulation in JCS, particularly within the framework of OW, emerges as a key innovation in the proposed 3D indoor visible light positioning algorithm [5].

The confluence of OWC and RF technologies in hybrid networks has ushered in sophisticated strategies for proactive resource allocation. By leveraging accurate knowledge of user locations, these networks can optimize resource allocation to improve both user experience and network efficiency [6]. This paradigm shift toward predictive resource management highlights the need for innovative solutions that accurately predict user mobility and seamlessly integrate disparate technologies. In parallel with developments in OWC, fiber optic technologies have emerged as a formidable medium for both long-distance communication and sensing. The application of artificial intelligence (AI) and machine learning (ML) methodologies has significantly enhanced the capabilities of fiber optic sensors, facilitating the detection of minute environmental changes with unprecedented precision [7]. This dual functionality extends the utility of fiber optics beyond telecommunications, paving the way for its application in environmental monitoring, infrastructure security, and beyond. OWC technologies, particularly VLC and optical sensing, play a key role in advancing traffic control systems and facilitating the integration of autonomous vehicles, as shown in Fig. 2. The dual use of LED-based lighting for illumination and data transmission offers a promising avenue for improving vehicular communication, navigation, and overall traffic efficiency [8]. Despite the potential, challenges related to LoS requirements, optical interference, and integration with existing communication networks remain to be addressed.

III. Challenges and future works

The integration of OWC and fiber technologies into future 6G wireless networks, while promising, presents a number of challenges that require concerted research and development efforts. Overcoming these challenges is critical to realizing the full potential of these technologies to enhance communication, sensing and localization capabilities in various sectors, includ- ing IoT, smart cities, healthcare and intelligent transportation systems.

Addressing the LoS requirement: A significant challenge in deploying OWC systems, particularly VLC, is the inherent LoS requirement between transmitters and receivers. This limitation limits the effectiveness of the system in environments with potential obstacles or non-direct paths, such as indoor spaces with complex layouts or urban environments with numerous obstacles. Future work should focus on innovative solutions to mitigate LoS limitations, including the development of advanced reflective materials, relay systems, and beam steering techniques to improve signal range and reliability.

Overcoming ambient light interference: The performance of OWC systems, especially in outdoor or well-lit indoor environments, can be severely degraded by ambient light sources. This interference can degrade the signal-to-noise ratio (SNR), which affects the reliability and efficiency o f data transmission. Research into advanced modulation schemes, filtering techniques and adaptive algorithms capable of dynamically compensating for ambient light variations is essential to mitigate these effects.

Integration with existing wireless technologies: Seamless integration of OWC and optical fiber t echnologies w ith existing RF-based communication systems is a significant challenge. This integration is critical to ensuring interoperability and maximizing the coverage, reliability and efficiency of next-generation wireless networks. Future work must address the development of hybrid network architectures, standardized communication protocols, and cross-layer optimization strategies to ensure smooth coexistence with existing technologies.

Scalability and cost-effectiveness: As the applications of OWC and optical fiber t echnologies e xpand, e nsuring the scalability and cost-effectiveness of these systems becomes imperative. Research should aim to develop cost-effective manufacturing processes for OWC and fiber optic components, as well as scalable network deployment strategies that can meet growing demands without exponential cost increases. This includes the exploration of novel materials, energy-efficient devices and automated deployment methods.

Improving sensing and localization accuracy: While OWC and optical fiber technologies offer significant potential for improving sensing and localization capabilities, achieving high levels of accuracy and reliability in diverse environments remains a challenge. Future research should focus on advanced algorithms and signal processing techniques that leverage AI and ML to improve the accuracy and robustness of sensing and localization functions under varying environmental conditions and in the presence of obstacles.

Security and privacy concerns: The use of OWC and optical fiber technologies for communication and sensing raises pertinent security and privacy concerns. The broadcast nature of optical signals and the potential sensitivity of sensed data require robust security protocols and encryption techniques to protect against unauthorized access and data breaches. Future work must address these concerns by developing secure communication frameworks and appropriate algorithms tailored to the unique characteristics of OWC and fiber optic systems.

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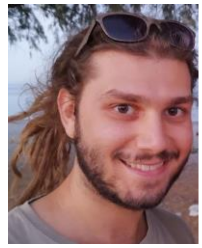

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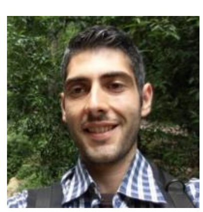

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