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European Cooperation in Science and Technology

EU COST ACTION on

Future Generation Optical Wireless Communications

NEWFOCUS

CA19111

White Papers

Editors: Z Ghassemlooy and M-A. Khalighi

June 2024

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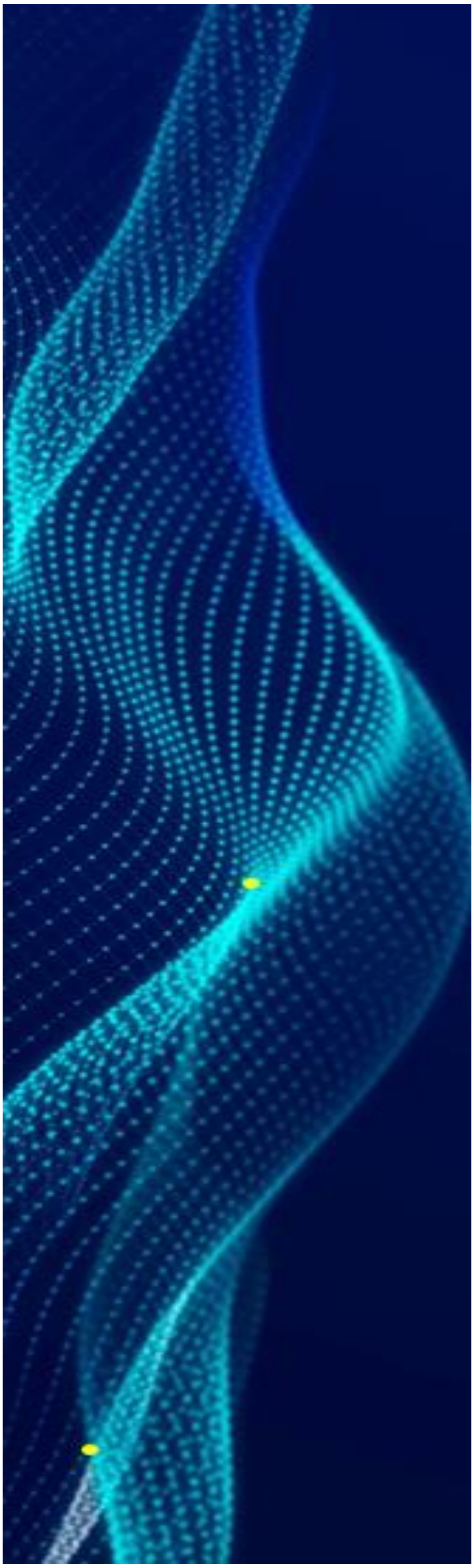


Contents

INTRODUCTION

The total wireless data traffic is predicted to triple in 2026 compared with 2021 [1], with a significant change in the content. In addition, wireless communication is expected to continue to evolve and improve in the future. This is because (i) the current wireless technologies cannot sustain the explosion of the wireless data 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; and (ii) the increasing demand for massive data traffic will require full coverage and heterogeneous networks, with high transmission data rates, ultra-low-latency and ultra-high reliability.

The fifth and sixth generation (5&6G) wireless networks and beyond are introducing radical changes to ensure the full realization of the smart Internet-of-Things (IoT) and Internet-of-everything (IoE) paradigms capabilities, virtual and augmented reality services, cloud-computing, network controlled robotics, etc. In addition, up to 5G, the data traffic in cellular networks is dominated by high-bandwidth video or streaming application. Therefore, new applications have already triggered evolution to radically different communication networks, which are dynamic, sustainable, intelligent, simple, reliable, and energy efficient.

Only 6G will be able to widely serve the exponential growth in connected devices (i.e., more than 500 billion) in 2030. 6G will propel the **4th industry revolution** enabled mainly by the IoT/IoE. It will utilise all the available frequency spectrums including optical bands; advanced physical and network layers solutions; and energy harvesting. Furthermore, 6G networks will support new classes of services, such as: (*i*) ***green and sustainable communication*** for terrestrial, non-terrestrial and underwater scenarios; (*ii*) ***convergence of sensing, localisation, communications, computing and control*** capabilities; (*iii*) ***reconfigurable and adaptable communication networks*** using reconfigurable metasurfaces; (*v*) ***five-sense communication***; (*vi*) ***digital twin and virtual and augmented reality***; (*vii*) **human-centric services**; and (*viii*) ***autonomous vehicle.***

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. Moreover, space is emerging as the new frontier in the next generation and beyond communication networks, where it offers high-speed wireless coverage to remote areas both in lands and sees. This activity is supported by the recent development of low-altitude Earth orbit satellite mega-constellations [2].

The enabling technologies that will support all the above applications include:

(i) A*ir-interface and data transmission* – I.e., dynamic and artificial intelligent (AI)-based spectrum sharing mostly in unlicensed bands; blockchain-based wireless access, which offer additional security leading to supporting multiple services at the cost of increased latency and the degree of scalability; cell-free architecture but with increased complexity, synchronization and channel state information as well as higher requirements for front- and back-haul links; multiple access such non-orthogonal multiple access, which takes advantage of the channel conditions to offer improved spectral efficiency); unmanned aerial vehicles (UAVs); and reconfigurable intelligent surface to tune the radio environment.

(ii) *Network architecture* – This includes (*i*) could and edge computing to meet the divers and dynamic requirements; (*ii*) network function virtualization, which simplify the network management but requires mapping from physical to the virtual and integration of different function; and (*iii*) software defined networks.

(iii) *Spectra integrated networks* – This includes sub-6 GHz; millimetre-wave (mmWave); terahertz (THz) and optical wireless technologies. Spectral integrated networks have several issues such as new key performance indicators (KPIs); channel modelling and measurement; and efficient resource management.

(iv) *Artificial intelligence and machine learning (ML)-based networks* – With self-evolution mechanism design and knowledge graph characterisation and implementation.

Optical wireless communication (OWC). **OWC** with greater bandwidth and denser distribution of massive antenna arrays, will play crucial roles can complement the highly utilized RF-based communication offering secure, high-quality and cost-effective means of transferring massive volume of data over short to very long distance. Due to increasing demand for high-speed wireless networks we have seen significant growth in research and development in OWC as well as the global market. The market is mostly driven by several factors including the rise in the use of massive IoT devices, the need for last-mile access connectivity, the demand for space-to-ground and intersatellite communications to name a few. Furthermore, OWC is envisaged to play an important role in wide area local area network, data centers, augmented- and virtual-reality, and heterogeneous systems by combined power-line communication, illumination, imaging systems, display, and tracking.

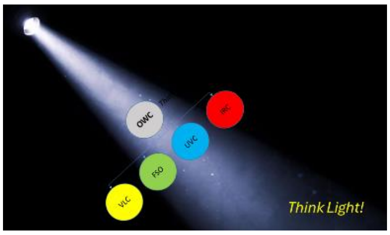
Horizon Europe the EU's ninth multiannual Framework Programme for research and innovation is the largest programme of its kind anywhere in the world with a total budget of €95 billion [3]. It promises more breakthroughs, discoveries, and world-firsts by taking great ideas from the lab to the market. The new framework will focus on four pillars:

I. **Pillar 1** – Excellent Science, aims to increase the EU's global scientific competitiveness.
II. **Pillar 2** - Global Challenges and European Industrial Competitiveness, which covers *(i) Health; (ii) culture, creativity, and inclusive society; (iii) civil security for society; (iv) digital, industry and space; (v) climate, energy, and mobility; and (vi) food, bioeconomy, natural resources, agriculture, and environment.*
III. **Pillar 3** - Innovative and Inclusivity in Europe, which aims to make Europe a frontrunner in market-creating innovation via the European Innovation Council.
IV. **Horizontal Pillar** - Widening participation and strengthening the European Research Area.

A significant part of **Pillar II** will be implemented through institutionalized partnerships, particularly in the areas of Mobility, Energy, Digital and Bio-based economy, which will also have separate work programmes. In this context, **the EU COST Action on Future Generation Optical Wireless Communications (NEWFOCUS)** [4] 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 **OWC** covering all three spectrum bands (i.e., **ultraviolet** (UV), **visible** and **infrared** (IR)) and to establish it as a complementary technology to the RF-based wireless systems in order to meet the demanding requirements of the fifth generation and the future 6G backhaul, access (non-terrestrial) and terrestrial networks. To achieve these, NEWFOCUS 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 IoT 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.



NEWFOCUS has contributed significantly to the development of OWC beyond classical communication, enhancing a deeper understanding of the technology and its applications as well as generating renewed interest within the scientific community. In addition, NEWFOCUS has ensured that OWC and its applications continued to transcend conventional high-speed data communication and make inroads into the areas of massive IoT in smart environments, integrated technologies of sensor-communications, positioning-communications, sensing-positioning-communications, quantum key distribution (QKD), single-photon counting Rxs, underwater communications, optical camera communications and hybrid RF-optical fiber-OWC and RF-mmWave-

OWC technologies as part of the next generation wireless networks. Note that the next-generation OWC will incorporate multiple functionalities and features requiring advancements across a wide range of fields, including materials, micro/nano devices, communication protocols and systems, air interface technologies, and AI/ML-based systems.

The focus of this **White Paper** is on the use of **OWC** as enabling technology in a range of links for for deployment in (*i*) smart-cities and intelligent transportation systems; (*ii*) first- and last-mile access and backhaul/fronthaul wireless networks; (*iii*) hybrid free-space optics/RF adaptive wireless connections; (*iv*) UAVs; (*v*) space-to-ground, inter-satellite, ground-to-air, and air-to-air communications; (*vi*) underwater communications; and (*vii*) network and protocol.

This document covers three main topics of OWC:

(i) General topics - This includes contributions on Optical Wireless Communication – The Context, by *Z. Ghassemlooy, et al*.; Current Status and Possible Directions to Gain Momentum in the Massive Adoption of OWC, by *A. A. Dowhuszko, et al*; Optical Technology for Joint Communication and Sensing, by *S. A. Tegos, et al*.; and The Highly-sensitive SPAD-based Optical Wireless Communication, by S. Huang, et al.

(ii) Short to medium range systems - The first three contributions are on visible light communications

(VLC) including On Signalling and Energy Efficiency of Visible Light Communication Systems, by *T. Gutema and W. Popoola*; Audio Signal Quality Assessment in Visible Light Communication, by *J. Galić, et al*.; Physics-based Modelling of LEDs and Phosphors Paves the Way to Boost VLC Performance, by *J-P Linnartz and P. Salvador*; and PHY Security in Visible Light Communications by *E. Panayirci, et al*. The next two articles are on Optical Camera Communication by *Z. Ghassemlooy, et al*.; and Practical Implementation of Outdoor Optical Camera Communication Systems with Simultaneous Video and Data Acquisition, by *V. Matus, et al*.

On application of OWC/VLC there are seven contributions: Visible Light Communications for Intelligent Transportation Systems, by *M. Uysal*; On the Use of Visible Light Communications in Intelligent Transportation Systems – From Road Vehicles to Trains, by *A. M. Vegni*; Optical Wireless Communications Technologies for Manufacturing in Industry 4.0, by *B. Ortega and V. Almenar*; OWC-based Smart Ocean Sensor Networks for Environmental Monitoring, by *I. C. Ijeh*; Unmanned Aerial Vehicles with Lightwave Technology for 6G Networks, by *P. D. Diamantoulakis, et al*.; Virtual Reality by *O. Bouchet*; and Optical Neural Networks with the Visible Light Communication Technology by *M. Hulea, et al*.

(iii) Medium to long range systems - The first three contributions are review types on Optical Wireless Communications – Medium to Long Range Applications by *Z. Ghassemlooy et al*.; Quantum Communications Over Free Space Optical Satellite Links: Challenges and Opportunities, by *A. A. Dowhuszko, et al*.; and Review of Low-Earth Orbit Satellite Quantum Key Distribution, by *D. Orsucci, et al*. The next five articles are on Atmospheric State Information for Long-range FSO Communication, by *N. Doelman, et al*.; Wavelength Division Multiplexing Free Space Optical Links, by *G. Cossu, et al*.; Free Space Optical Communication in the Mid-IR for Future Long-range Terrestrial and Space Applications, by *X. Pang and C. Sirtori*; Review of Hybrid Optical-Radio Inter-Satellite Links in 6G NTN Including Quantum Security, by *J. Bas and M. Amay*; Perspectives for Global-scale Quantum Key Distribution via Uplink to Geostationary Satellites, by *D. Orsucci, et al.* The last paper on IPv6-based IoT in 2025 by *L Ladid* that discusses how IPv6 can enable and sustain the growth rate of the IoT and offers a future-proof solution.

We hope that this collection of White Papers will serve as a valuable resource for a better understanding of the OWC technology highlighting some of the features, issues, and research works carried out in emerging application areas as well as promoting further research, and development in the successful deployment of OWC systems as a protuberant complementary to RF-based technologies in the 5G&6G and beyond heterogeneous wireless networks. Note that the future of wireless communication technology looks very promising and with continued advancements it will provide new opportunities for wireless communications; wireless networks; wireless sensors; wireless positioning; wireless sensing, positioning and communications; and wireless charging.

Finally, 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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General Topics

OPTICAL WIRELESS COMMUNICATION – THE CONTEXT

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INTRODUCTION

Globally, the society that we are living in is changing rapidly and becoming more data-centric, data-dependent, and fully automated with the aim of improving productivity and the quality of life. In a fully automated and intelligent world the IoT will play a critical role in connecting billions of physical devices in the fabric of society (i.e., people, machines, homes, offices, industry, cities, environments, etc) to sense, collect and exchange data, and improving interactions between devices across various sectors, such as manufacturing, the connected home, transportation, medical, and agriculture.

The widespread uptake of Industry 4.0 and the emerging smart environments (cities, factories, offices, homes, etc.) requires wireless IoT devices that can collect data and transmit them to a central location via telecommunication networks (particularly wireless networks). Within this context, 5G/6G wireless networks are aiming to offer full realization of the IoT paradigm with ML capabilities for connecting not just people, but also people-to-vehicles, people-to-devices, machine-to-machine, sensors, wearables, cloud resources, robots, etc. Therefore, in such challenging environments, there is the need for radically new telecommunication networks with key features of utilizing new spectrums, disruptive technologies, ML, enabling technologies, energy efficiency, sustainability, etc. Enabling technologies and solutions include mmWave (mostly unregulated bands up to 90 GHz) and THz bands; cell-free networks; cognitive radio systems; massive multiple-input and multiple-output (MIMO); three dimensions (3D) network architectures; femtocells and offloading solutions; green wireless technologies with energy harvesting features; and OWC.

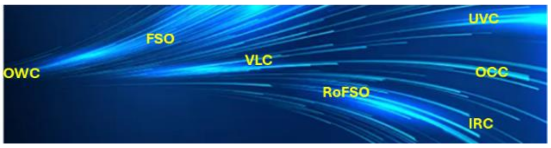
5G comprising of ultra-dense heterogeneous networks mostly relies on revolutionary technologies such as mmWave, network function virtualization, software-defined networking (SDN) and network slicing, as well as MIMO, to make a significant improvement in the transmission data rates (by × 1000), reliability, latency and connection density (by × 1000) compared with the pre-5G systems [2]. 5G is used in a wide range of applications, which can be broadly categorized into three main service classes of enhanced mobile broadband (eMBB) with data rates exceeding 1 Gbps for mobile users, ultra-reliable low-latency communications (URLLC) with high reliability (99.999%) and low latency (around 1 ms), and massive machine-type communications (mMTC) with a high number of connected devices supported in IoT deployments (up to 10^6 devices per km^2).

The future 6G wireless networks should serve a range of industrial applications, such as manufacturing, healthcare, agriculture, art and culture, intelligent transportation systems, etc., and therefore must meet high requirements in terms of communication reliability (> 99.999%), latency (≤ 1ms), scalability (1 $Tbps/m^2$), energy efficiency and consider the ecosystem too [2]. This will pose new challenges to the service providers in upgrading the existing communication networks to ensure compatibility and the quality of services at low cost, which becomes highly demanding in urban areas, where front- and back-haul access networks will increase strain on the existing networks. In 6G and beyond, the integration of radio and optical wireless technologies in access networks (front- and back-haul links) will be critical in providing the requirements, particularly for eMBB, URLLC and mMTC services. Regardless of the technology (5G or 6G) being adopted, there are a few approaches to increase the capacity of wireless networks including (*i*) release of new spectrums and therefore more bandwidth, which is costly; (*ii*) using more nodes, which can be done via cell splitting, which is complex and costly. Note that doubling the infrastructure will not lead to doubling the revenue; and (*iii*) improving the spectral efficiency, which has been done continuously over the years, but is slowing down in recent years.

Most existing wireless communication networks solely rely on the use of conventional RF-based technology to convey information. However, the RF technology is currently under pressure to meet the ever-growing demand for the spectrum to cater to new application areas such as massive MIMO, machine-type smart communication for autonomous systems, augmented reality, and virtual reality. Consequently, it is imperative to investigate new materials, devices, and front-end architectures for wireless connectivity, as well as novel as well as revolutionary communication and computing paradigms. The new potential candidate technologies for 6G and beyond include

reconfigurable intelligent surfaces, i.e., artificial planar structures with integrated electronic circuits, which can be programmed to control the incoming electromagnetic field in a wide range of functionalities, and the complimentary **optical wireless technology**.

OWC



Information and communication technologies contribute about 3% to the global emission of greenhouse gas, which can be significantly reduced by developing energy-efficient technology and standards [3]. Additionally, when designing the next-generation communication networks the need for network devices and equipment with lower carbon footprints must be considered. OWC can be adopted as a potential complementary technology, which will contribute to the reduced carbon footprints, that meet the demands for higher transmission throughputs in sustainable smart environments.

The OWC technologies include **free space optical (FSO)** communications (mostly IR, but both visible and UV bands can also be used); **visible light communication (VLC),** which offers the potential of using the light emitting diode (LED)-based lighting infrastructure to establish all-optical wireless networks for data communication, positioning, and sensing mostly in indoor environments and with limited use in outdoor applications at the moment; **optical camera communication (OCC)** that can be used with both FSO and VLC systems in indoor and outdoor applications with reduced interference and high SNR; and **OWC networking** using a combination of FSO, VLC, OCC, and RF-based schemes. Note that, indoor OWC systems are more sustainable due to their relatively lower transmit power and therefore less harmful effects compared with RF (particularly mmWave) communication schemes.

OWC technology could be employed in (*a*) **space** for ground-to-satellite, satellite-to-ground, inter-satellite; (*b*) **terrestrial** (indoor and outdoor including industry, healthcare, trains. railway and bus stations, airports and aircraft, transportation, homes, offices, shopping malls,), where most Internet traffic originates and terminates in indoor environments; and (*c*) **underwater**, where RF technologies are not the best option. The introduction of OWC technology not only simplifies the provision of scalable, secure, and sustainable wireless systems but also facilitates the possibility of (*i*) **optical positioning** in indoor environments, where the use of RF-based global positioning systems (GPS) is very limited and in certain environments (tunnels, underground, etc) not possible at all; (*ii*) **sensing**; (*iii*) **power transfer** for zero IoT devices for context-aware applications; and (*iv*) **releasing the RF spectrum** for use in applications areas where mobility is essential and OWC cannot be employed. Compared to state-of-the-art solutions using different portions of the RF spectrum (i.e., sub-6 GHz and mmWave bands), OWC offers three-fold gains of:

- **Ultra-densification -** Deploying an extremely large number of nodes, co-located even in the same room, without the use of advanced signal processing algorithms for interference management.
- **Interaction with humans –** Using the visible light spectrum band (i.e., between 380 and 750 nm) for illuminations, sensing, and localization in indoor/underground/tunnels environments in which lights are always on, and RF-based positioning systems cannot be utilized.
- **Wideband unlicensed spectrum -** Enables high point-to-point data rates when using laser-based light sources (i.e., in outdoor FSO applications), as well as high-sensing accuracy when using white LEDs for ranging and imaging. When compared to the RF signal power in the sub-mmWave bands (i.e., beyond 100 GHz), strong optical power is much easier to generate in both visible and IR bands.

Note that, in OWC the optical spectrum is much wider and is license-free, the maximum transmit power can be much higher than that allowed in RF bands, the level of interference is much lower than in RF-based systems, and the link security at the PHY is relatively better than RF links. In addition, hybrid wireless systems based on the integration of two or more wireless technologies, which can effectively exploit the cross-spectrum and cross-medium advantages of both OWC and mmWave technologies, may offer an effective solution with enhanced features overcoming the limitations of individual wireless technologies. The hybrid wireless systems can provide seamless connectivity between fixed and wireless networks and can deliver services regardless of the fixed or mobile network. The **RF/OWC hybrid** system provides convergence or integration of OWC and RF networks (fixed or mobile) in several applications.

CHALLENGES AND FUTURE RESEARCH AREAS

Note that, while OWC offers many interesting features compared with RF technology, there are still several important and fundamental challenges and issues, see below, that need investigating to make this technology viable and applicable.

- *Channel capacity* and *channel modelling* – To develop a new theory given that optical signal must be positive and real and therefore the classic Shannonian theory is not applicable, and to better understand the wavelength-dependent reflectance and absorption of objects and materials in indoor environments.

- *Resource and spectrum utilization* – The optical spectrum is three orders of magnitude larger than the entire RF spectrum when using low bandwidth and wide emission spectrum LED light sources.

- *Link power budget and limited Rx sensitivity* – Considering the widely spread transmit optical beam (from standard LEDs) and small size photodetectors for high-speed applications, respectively.

- *Uplinks in VLC* – There is no clear idea on this and whether to use visible and/or IR bands as well as wireless fidelity (WiFi). Consideration should be given to energy power usage since the uplink optical Txs are very close to the users, as well as no flickering.

- *Blocking/shadowing, mobility, pointing, and tracking* - In both indoor and outdoor environments. Support horizontal and vertical handovers (in hybrid VLC-WiFi networks) to ensure seamless communications.

- *The eye and skin safety* – This is critical when using a high-power point source in indoor environments. The integration of compact and small optical concentrators in optical Rxs to improve the SNR in systems using broad-beam light sources.

- *Networking and protocols* – To manage nested small cells (i.e., pico- and femto-cell) and provide seamless integration with the existing RF-based wireless and optical fiber-based backbone infrastructure. As well as the need for energy-efficient MAC protocol and green routing algorithms.

- *Link availability* – Under all-weather conditions mostly FSO systems for outdoor applications.

- *Security* – Using novel technologies such as QKD-based combined with innate physical security can result in two-fold information secrecy.

- *A dynamic architecture and network function analysis* – Where future OWC networks should have a dynamic topology in nature with a cross-layer approach because of network densification (particularly in urban areas), where the end-users will have multiple connections.

- *Resource and interference management* - Support many emerging new applications, e.g., using SDN with ML for real-time system management.

- *Energy harvesting* – OWC modules should be either self-powered, use ultra-long-life batteries, power over ethernet, or mains-powered, therefore is no need to keep replacing batteries.

- *Standards* – More contributions from academia and industry to the existing standards on short-to-long range OWC systems.

- *Optical beamforming/beam steering optimization using ML* – This facilitated allocating the optical radiation to specific users, thus improving SNR and security as well as reducing interference.

- *New devices* – Investigation of new devices with improved optical and electrical characteristics that will meet the energy, bandwidth, sustainability, and adaptability requirements of the next-generation wireless networks.

- *Simple and low-cost plug-and-use modules* – This is most important in VLC and OCC systems if they are going to be widely adopted by the industry and the end-users.

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CURRENT STATUS AND POSSIBLE DIRECTIONS TO GAIN MOMENTUM IN THE MASSIVE ADOPTION OF OWC

Alexi A. Dowhuszko, Iman Tavakkolnia, and Panagiotis D. Diamantoulakis

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 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 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 intro- duction of white LEDs for indoor illumination, the development of OWC technologies gained momentum again with focus on the provision of optical wireless access in indoor scenarios.

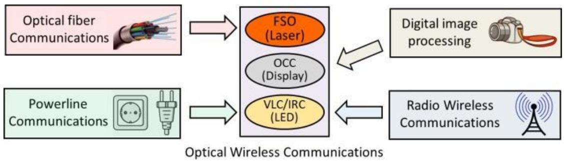

Fig. 1. Areas of communications engineering that are influencing the development of OWC technology. Terminology: FSO, OCC, VLC, and Infrared Communications (IRC).

The challenges of implementing OWC systems in practice have many similarities to the ones faced in other kinds of 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 known as the "air" or the "free space". However, the light sources (LEDs or LDs) and detectors (i.e., photodiodes (PDs)) that are used in OWC transmitters (Txs) and receivers (Rxs), 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 PD, 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 the Rx in an 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 PDs. In the Tx 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 (red, green, blue (RGB)) LED technologies, the same aggregated white light that 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.

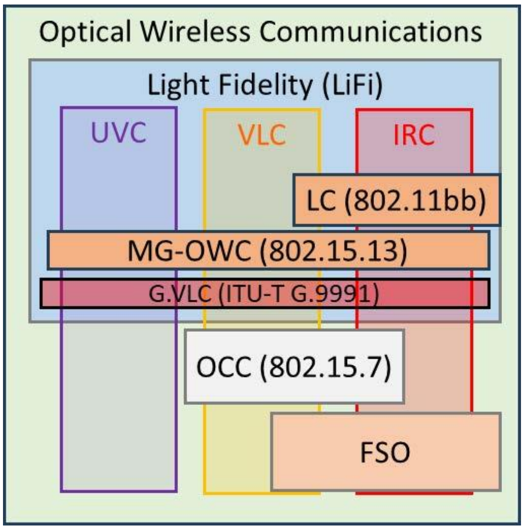

Fig. 2. Summary of the terminology used by the academic and the industrial sector to classify the different kinds of OWC systems that can be implemented. The relation that exists between each of these terms are also visualized.

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 stands as the broadest term, encompassing any wireless communication system leveraging segments of the electromagnetic spectrum referred to as "light," including UV, visible, and IR bands.
- 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 IR (uplink and downlink) spectra is employed. LiFi can be conceptualized as the optical counterpart to radio wireless local area network (WLAN).
- 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 Tx, thereby enabling the accommodation of both intensity modulation/direct detection (IM/DD) and coherent communications methodologies.
- 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 Tx device. Consequently, joint illumination and communication (e.g., broadcasting) represent the typical applications for VLC.
- 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 and 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 counter-parts. 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 – 1000nm band. IEEE 802.11bb uses the term LC to refer at its OWC system that achieves a bidirectional communication with data rate transmissions ranging from 10Mbps 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 20 used in this standard to support data rates as high as 10 Gbps. Being based on RF communication, 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 aimed 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 PHY with data rates up to 2 Gbps, which is supported by a MaxLinear baseband processor chipset. The existence 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 promis- ing. 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: pure- LiFi 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., smart- phones, 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 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.

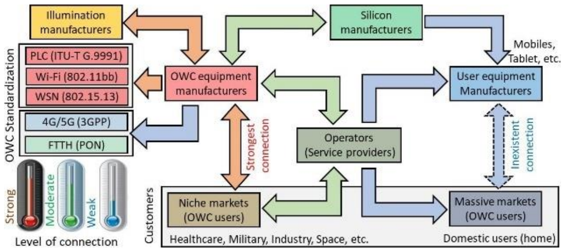

Fig. 3. Stakeholders and existing/under-development connections that are needed to pave the way to the massive adoption of OWC technology in domestic markets. Color of arrows show the presence of strong (red), moderate (green) and weak (blue) interest. Arrow directions show the interest of stakeholders.

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 spec-trum 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; and (*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 IR 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 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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ON 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

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 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, 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 RF technology in hybrid networks offers a promising solution to the challenges of current and future communication needs [3]. OWC uses 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.

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 MIMO technologies. These shared advantages lay the groundwork for the development of systems that leverage both communication and sensing capabilities, albeit with inherent challenges related to waveform tradeoffs and sensor performance metrics.

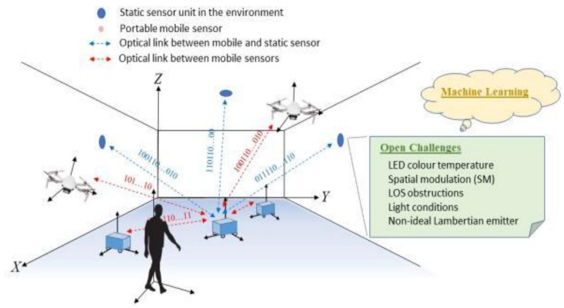

Fig. 1. Centralized optical local positioning system.

The use of OWC, particularly through VLC and IR techniques, has led to advances in 3D sensing and localization, as shown in Fig. 1. Innovations such as spatial modulation (SM) 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 SM 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 AI and 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.

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, including IoT, smart cities, healthcare and intelligent transportation systems.

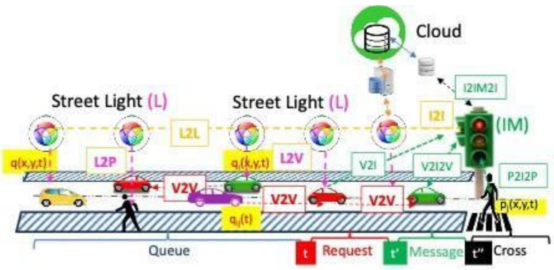

Fig. 2. OWC for adaptive traffic control.

Addressing the LoS requirement: A significant challenge in deploying OWC systems, particularly VLC, is the inherent LoS requirement between Txs and Rxs. 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 SNR, which affects the reliability and efficiency of 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 technologies with 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 technologies expand, ensuring 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 op- tical 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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HIGHLY-SENSITIVE SPAD-BASED OPTICAL WIRELESS COMMUNICATION

Shenjie Huang, Mohammad-Ali Khalighi, and Majid Safari

INTRODUCTION

We have already witnessed the successful standardisation and deployment of the 5G wireless communication networks. However, the rapid emergence and evolution of smart products, interactive services, and intelligent applications result in a significant need for high-speed wireless communication. It is anticipated that the current 5G technology will be inadequate in meeting the demands of future communication requirements beyond the year 2030 and people have started to investigate what the future 6G will be. It is expected that 6G will provide key features including ultra-high speed, nearly 100% geographical coverage, sub-centimeter geo-location accuracy, enhanced energy efficiency, and high intelligence levels. These key features will greatly accelerate the development of the enabling technologies for smart cities such as the Internet of Things, autonomous vehicles, and intelligent transportation systems. All available spectra are expected to be explored in 6G to boost the data rates, including the sub-6 GHz, mmWave, THz, and optical frequency bands. Therefore, **OWC** is envisioned to play a pivotal role in future wireless networks.

Over the past few decades, the main applications of OWC, which have been extensively investigated within both academic and industry communities, include space communication, terrestrial **FSO communication**, **indoor VLC**, **OCC**, and **underwater OWC (UOWC)**. Despite having three orders of magnitude more spectrum resources compared to its RF counterparts, OWC still faces significant challenges that must be addressed before it can be widely deployed, in particular, the occasional outages due to fluctuations in LoS received power. Such power fluctuation can be introduced by various factors. Specifically, for indoor VLC, it can be caused by user mobility, device orientation, random blockage, and dimming control, while for outdoor FSO, it can result from turbulence effects, adverse weather conditions, and transceiver vibration. Highly sensitive Rxs, such as **single-photon avalanche diodes (SPADs)** can be employed to effectively mitigate power outage issue and improve reliability. SPADs also have the important advantages of low cost, weight, and operation voltage, rendering them highly suitable for OWC applications.

STATE OF THE ART

The photon counting capability of a SPAD is achieved by biasing the traditional linear PD above the breakdown voltage to operate in the Geiger mode. When a photon arrives, the SPAD can detect it and initiate an avalanche process which produces a striking current pulse. Compared to the traditional linear photodetectors such as positive-intrinsic-negative (PIN) PD and avalanche photodiode (APD), a SPAD has the advantage of significantly higher Rx gain (on the order of 10^6). While SPAD-based Rxs can offer single photon sensitivity, they need to be quenched after each avalanche triggered by a photon detection. During this quenching period, which is known as the *dead time*, the SPAD becomes temporarily insensitive to any incident photon arrivals, because the bias voltage of SPAD has not yet recovered to the operating level.

Depending on the adopted quenching strategies, SPADs can be categorised into two types, namely, passive quenching (PQ) and active quenching (AQ). AQ SPADs use active circuits to detect the avalanche pulse and then quench it, followed by resetting the SPAD after an accurate hold-off time, while PQ SPADs quench the avalanche currents by simply flowing through quenching resistors without using active circuitry. For PQ SPADs, any photon arrival during the dead time can extend its duration. In contrast, AQ SPADs exhibit constant and short dead times. Despite the superior performance of AQ SPADs, the current commercial and research and development (R&D) SPAD Rxs still predominantly rely on PQ technology due to its cost-effectiveness and scalability.

SPAD has a wide range of applications such as in LiDAR, quantum communication, positron emission tomography and time-of-flight and fluorescence lifetime imaging. In recent years, there has been a growing interest in exploring the potential application of SPAD in the context of OWC. Specifically, in 2013, Fisher *et al.* introduced a reconfigurable 32×32 SPAD array Rx designed in standard 130 nm CMOS technology and studied its properties for VLC [1]. Later, numerous studies have been conducted to investigate SPAD-based VLC systems [2]. More recently, the applications of SPAD in UOWC and FSO were also studied in [3-4] and references therein. Although SPAD can greatly improve the Rx sensitivity in OWC and overcome outages caused by low received power, its performance is strongly limited by the dead time, especially in high received power scenarios. From the communication point of view, dead time mainly introduces two main impairments: nonlinear distortion [4] and intersymbol interference (ISI) [5].

Many research efforts have focused on mitigating the dead time effects and enhancing the throughput of SPAD OWC through the exploration of innovative Rx designs, decoding schemes, and signal-processing techniques. In particular, a hybrid SPAD/PD Rx which leverages both the high sensitivity of SPADs and the high data rate of linear PDs to achieve superior performance has been proposed in [4]. The hybrid Rx, as shown in Fig.1, consists of both PIN PD and SPAD array detectors and possesses dual operation modes. It can adaptively switch between the high sensitivity (SPAD) mode and the high data rate (PIN PD) mode depending on the incident optical power. Other works have explored the enhancement of performance improvement in SPAD OWC through signal-processing techniques, thus avoiding the need for additional hardware complexity. Because of the nonlinear nature of the dead-time-induced ISI, the commonly used linear equalization techniques cannot provide decent performance in SPAD OWC. Therefore, the adoption of nonlinear equalizers becomes crucial in high-speed SPAD OWC. The current record experimental data rate achieved by SPAD OWC in the open literature is 5 Gbps, which was recently reported in [5]. The achievement of this high data rate was enabled by the integration of several techniques, including optical OFDM, nonlinear equalization, peak-to-average power ratio optimization, and adaptive bit and energy loading.

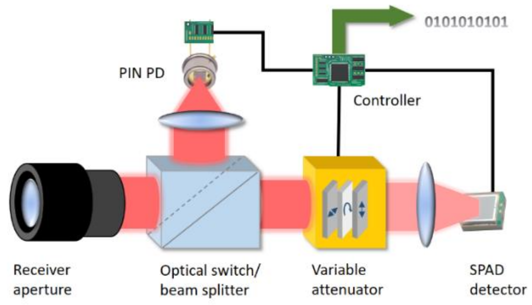

Fig. 1. The schematic diagram of the hybrid SPAD/PD Rx.

CHALLENGES AND FUTURE WORKS

Although recent theoretical and experimental studies have already illustrated the feasibility and advantages of incorporating SPADs in OWC, further efforts are still needed to address the existing challenges before its commercialization and widespread adoption. SPAD is an imperfect photon-counting Rx due to the presence of some non-ideal effects. One critical challenge that needs to be overcome is the development of cost-effective SPAD detectors with superior specifications, such as short dead time, high photon detection efficiency, as well as low dark count rate, after-pulsing, and crosstalk probability. All these factors can affect communication performance and need to be improved to realize a high Rx sensitivity approaching the quantum limit. Especially, considerable research efforts should be devoted to developing highly efficient SPAD detectors operating in the IR, e.g., InGaAs/InP SPADs for 1550 nm, which are promising for long-distance OWC. In addition, the current research mainly focuses on the application of SPAD in VLC, FSO and UOWC. There is a notable absence of studies investigating its use in other OWC applications, such as OCC and optical vehicular communication. Therefore, it is imperative to conduct further research to explore the potential of SPAD in such applications.

Developing simple yet efficient techniques to combat the imperfections of SPADs, such as dead time and after pulsing, is also a challenge that requires further investigation. Although several techniques have already been proposed in the literature, they suffer from some limitations, such as high complexity and limited efficacy. To address these issues, one promising research direction could be developing machine learning techniques tailored to SPAD-based OWC.

Most of the SPAD OWC works in the literature employed on-off keying (OOK) as the modulation scheme, mainly because of the limited dynamic range of the SPAD Rxs caused by dead time and small array size. Recently, because larger array SPAD detectors with low dead time become available, people have started to explore the application of higher-order modulation schemes, such as optical OFDM, in SPAD OWC. However, novel spectrum-efficient modulation schemes designed based on the unique properties of SPAD are highly desirable and are expected to achieve superior performance compared to traditional schemes. Other open challenges include the derivation of accurate photon counting models and the development of advanced decoding techniques. It can be anticipated that more rapid deployment of SPAD-based OWC is feasible if all the aforementioned challenges can be successfully addressed.

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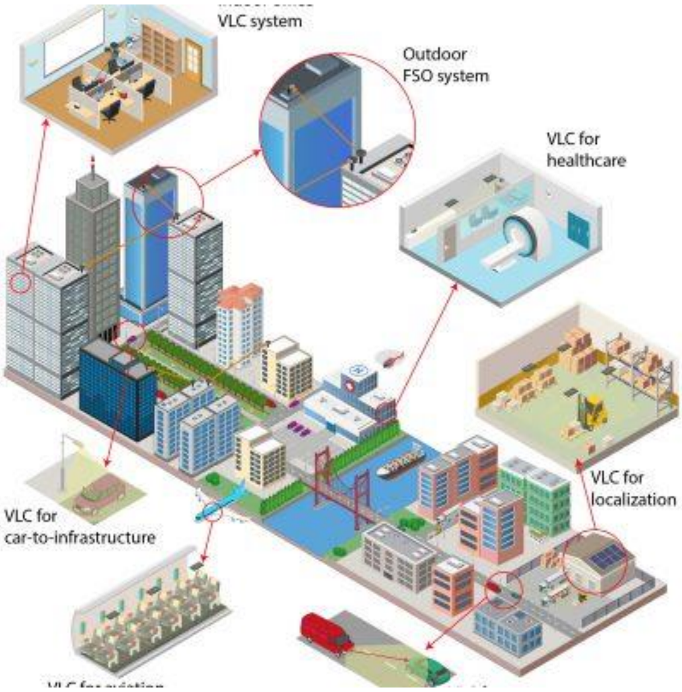
Short-to-medium Range Links



ON SIGNALLING AND ENERGY EFFICIENCY OF VISIBLE LIGHT COMMUNICATION SYSTEMS

Tilahun Gutema and Wasiu Popoola

INTRODUCTION

A **VLC** system that uses low-cost LEDs is a viable approach to complement the existing radio-based communication systems. Energy-efficiency, low-cost, and ubiquity of LEDs and a license-free spectrum make VLC a suitable candidate for low-power systems as well. However, achieving the potential of VLC requires a good understanding of the right signalling and waveform design for any given applications. In the case of resource-constrained wireless network, energy efficiency and robustness are paramount. A low-rate wireless network requires simple, low-cost, and reliable communication with limited power consumption. For such networks, energy efficiency is of significant importance to prolong battery life in applications such as IoT. Equally vital is the robustness of the link to noise and other channel impairments.

Thus, a key challenge in designing and optimising a VLC system is to improve its energy and spectral efficiency [1]. Energy efficiency is important as it can help to reduce the power consumption and operating costs of VLC systems, while spectral efficiency is crucial for supporting many users or applications in each frequency band. An important theoretical framework for understanding the relationship between SNR, bandwidth and the capacity of a communication channel is the ultimate capacity limit formulated by Shannon in 1948 [2]. According to Shannon's theory, the capacity of a communication channel is a linear function of the bandwidth, but a logarithmic function of the SNR. This means that increasing the bandwidth of a VLC system can significantly increase its capacity while increasing the SNR has a less pronounced effect. As a result, it is important to optimise not only the SNR but also the bandwidth of a VLC system to maximise its capacity.

STATE OF THE ART

Significant research effort has been geared towards the development of high-speed VLC. Such systems must address the challenges associated with the relatively low modulation bandwidth of commercial LEDs. Various techniques such as pre- and post-equalisation, high-order modulation signalling have been explored to optimise the spectral efficiency and achieve high data rates in the order of Gb/s using a single LED. It has also been demonstrated that the LED modulation bandwidth increases as bias current increases until it saturates. However, an LED is a nonlinear device. That is, its emitted optical power as a function of the driving current is not linear. Consequently, driving the LED in the nonlinear region distorts the transmitted signal and deteriorates the system performance. Therefore, it is imperative to optimise the DC bias point of an LED to benefit from increasing bandwidth at driving current while minimising any nonlinear distortion associated with operating beyond the dynamic range of the LED as reported in [3].

Figure 1 shows an example of this optimisation in terms of the achieved bit rate per channel use at different bias current for LED VLMB1500-GS08. This illustrates that as the bias current is increased, the increase in modulation bandwidth translates to increasing transmission rate but beyond the optimum point, the bandwidth increase is offset by the reduced SNR and increased nonlinearity/distortion.

Another approach is to optimise the SNR term and maximise the available channel capacity for any given bandwidth that is available for use. This can be realised by adjusting the distribution of source symbols using signal-shaping techniques. Conventional data transmission schemes transmit each symbol with equal probability, which is not optimal for the additive white Gaussian noise (AWGN) channel [4]. By using signal-shaping techniques, it is possible to optimise the distribution of source symbols and improve the spectral efficiency of a VLC system. This can help to close the gap between the spectral efficiency of a VLC system and Shannon's channel capacity. A viable way to achieving this is probabilistic shaping.

The PS approach reduces the amount of symbol energy required in transmission. This is because PS provides a Gaussian-like distribution over the signal constellation. Therefore, low-energy symbols, which have a lower standard deviation in the Gaussian-like distribution, are transmitted more frequently than high-energy symbol, as graphically illustrated in Fig. 2. This reduction in average symbol energy at a specific error rate, compared to a uniform distribution, is known as shaping gain. The resulting shaping gain can be used to increase the SNR, which results in increased noise resilience and a higher achievable information rate. Thus, PS is a valuable technique for improving the performance of VLC systems, particularly in high-speed applications.

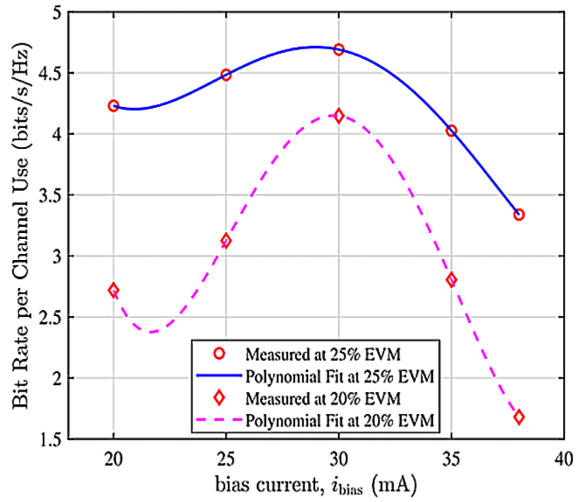


Fig. 1: Achieved bit rate per channel use considering 25% and 20% reference error vector magnitude (EVM) at different bias currents for LED VLMB1500-GS08.

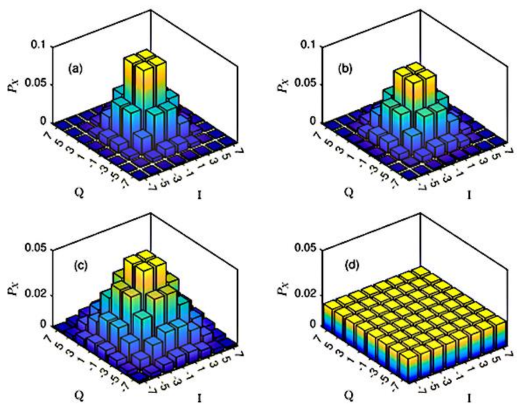


Fig. 2: Graphical illustration for probabilistic shaped with four different entropy values (a) H = 4.5 bit/symbol, (b) H = 4.80 bit/symbol, (c) H = 5.40 bit/symbol, (d) H = 6.00 bit/symbol (uniform distribution)

Signalling methods to achieving efficient use of available energy in VLC systems include orthogonal modulation schemes. These schemes have applications in low-power and low-rate networks. However, orthogonal modulations sacrifice spectral efficiency to approach Shannon's limit. As a result, it is important to carefully balance the trade-off between energy efficiency and spectral efficiency when designing VLC systems using orthogonal modulations.

Signalling techniques such as OOK, and *M*-ary pulse amplitude modulation (M-PAM) are simple to implement and have been studied extensively [5]. While it is possible to achieve a 1 bit/s/Hz spectral efficiency with OOK, it is generally regarded as energy inefficient. Spectral efficiency of $\log_2 M$ bit/s/Hz can be achieved with *M*-PAM but the required SNR increases with increasing *M*. On the other hand, in orthogonal modulation techniques such as *M*-ary pulse-position modulation (*M*-PPM) and frequency shift keying (*M*-FSK), the energy efficiency improves as *M* increases at an expense of spectral efficiency. Moreover, PPM has a peak-to-mean optical power ratio and is very sensitive to Rx synchronisation that requires complex equalisation techniques to mitigate. On the other hand, FSK waveform has a constant envelope and requires relatively simpler equalisation methods. For these reasons, previous studies, such as [6], have considered the energy-efficient FSK based VLC for low data rate and low-power IoT applications. However, in frequency selective channels and applications where the modulation bandwidth is limited and the overall link end-to-end response is non-flat, such as in VLC, the performance of FSK-based systems begins to degrade. That is because FSK symbols mapped onto frequency region where the channel attenuation is larger will lead to erroneous detection.

CHALLENGES AND FUTURE WORK

An emerging signalling approach for VLC is chirp modulation in which a symbol is mapped to all frequencies linearly within the bandwidth. Consequently, the chirp signalling is resilient as the symbol energy not concentrated in a single subcarrier signal frequency but spread across a progressively increasing range of frequencies within the symbol duration. As a result, the entire energy of a data symbol is somewhat shielded from severe attenuation suffered by any single subcarrier signal frequency. Thus, 'chirping' the symbol energy over a range of subcarrier signal frequencies offers resilience to the combined effects of the channel and limitation of the front-end devices.

The application of VLC in addressing the wireless communication challenges in the subsea channel continue to attract attention. Water absorption, multiple scattering and turbulence pose serious challenges for underwater VLC though. Other emerging trends in the VLC research include the use of machine learning in signal detection and channel mitigation and heterogeneous network that combines multiple bearers. However, for VLC to realise its potential, there will need to be a move away from the LoS dominated studies to beyond LoS VLC systems.

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AUDIO SIGNAL QUALITY ASSESSMENT IN VISIBLE LIGHT COMMUNICATION

Jovan Galić, Milan Mlađen, Gordana Gardašević, Milica Petković, Boris Malčić, and Slavko Šajić

INTRODUCTION

The continuous increase in the amount of traffic in the 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, 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 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.

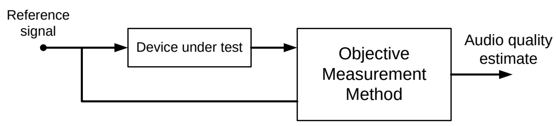

Fig. 1. The block diagram of the basic PEAQ algorithm.

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 Tx includes a signal processing circuit, Tx driver circuit, LED, and optical antenna. The Rx contains a PD, 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 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 Tx and the Rx are depicted in Fig. 2. The Tx 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 Rx consists of a PD, a trans-impedance amplifier, and an amplifier. Since the PD 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 I.

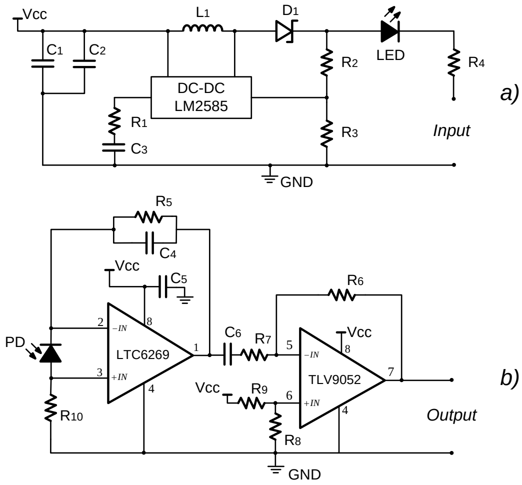

Fig. 2. The circuit diagrams of: (a) the Tx, and (b) the Rx.

Table I − 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 Tx, the Rx, the voltage source, and the audio analyzer. 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.

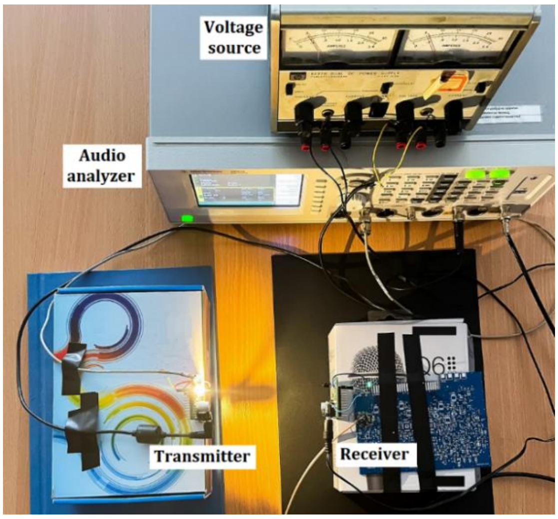

Fig. 3. The experimental testbed.

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

J-P Linnartz and P.Salvador

INTRODUCTION

Radio communication has seen tremendous advancements 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 OOK and Morse code were prevalent. Presently, there's swift progress in intensity modulated OWC with 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 seemed 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.

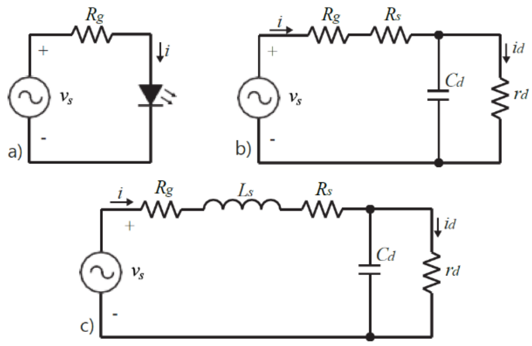


Fig. 1. LED Electrical Models: (a) target circuit, (b) basic (1st-order) model, and (c) advanced (2nd-order) model.

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.

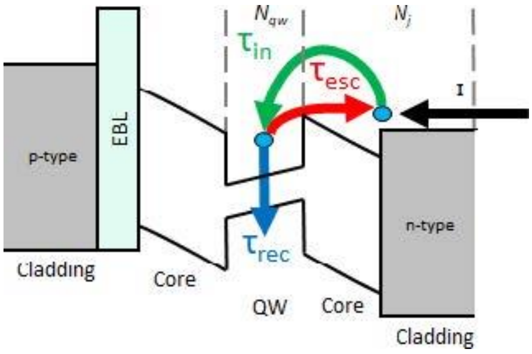
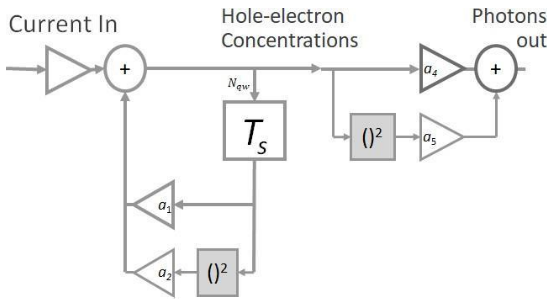


Fig. 2. Electron-hole recombination in an LED.

Phosphor-based LEDs operate on the principle of con- verting 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].

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

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.

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 PDs.

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

- 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 PHY standards that are better suited for optical wireless communication, including the mitigation of LED artefacts.

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PHY SECURITY FOR VISIBLE LIGHT COMMUNICATIONS IN THE ERA OF 6G

Erdal Panayirci, Panagiotis D. Diamantoulaki,s and Harald Haas

INTRODUCTION

Security, privacy and trustworthiness by design are envisioned to be the key objectives of a novel class services in the era of the 6G of wireless networks [1]. A brief presentation of all the envisioned classes of services in the era of 6G is presented in Fig. 1. In order to achieve the KPIs of the classes of services in the era of 6G and beyond, the use of physical layer security (PLS), except of increasing the overall system's security, is expected to facilitate the provision of other classes of services in 6G, including ultra-massive machine-type communication, energy sustainable communication, and extremely reliable and low-latency communication. This is because the approach of PLS can play a vital role in reducing both the latency as well as the complexity of novel security standards. In the meanwhile, it is expected that the dramatic increase in high data rate services will continue its trend to meet the demands of 6G networks. Thus, the use of PLS in communication systems that use higher frequency bands is of paramount importance, to mitigate the spectrum (especially of the convenient sub-6 GHz frequency band) saturation, which also negatively affects PLS.

Optical wireless communications and **visible light communications** offer attractive features such as high capacity, robustness to electromagnetic interference, a high degree of spatial confinement, inherent security, and unlicensed spectrum. Depending on the intended application, VLC can serve as a powerful complementary technology to the existing ones, such as the wireless body area network and personal area network, wireless local area network, vehicular area network, and underwater hybrid acoustic / VLC underwater sensor network and it will also be useful in scenarios in which traditional RF communication is less effective such as in airplanes, underwater communications, healthcare zones, etc.

During the past few years, PLS in VLC networks has emerged as a promising approach to complement conventional encryption techniques and provide a first line of defence against eavesdropping attacks. The key idea behind PLS is to utilize the intrinsic properties of the VLC channel to realize enhanced physical layer (PHY) security, without reliance on upper-layer encryption techniques. We use the **secrecy capacity** as a performance measure to determine the maximum communication rate that guarantees reliable reception of the secret message by the authorized Rx.

The evolution toward 6G wireless communications poses new and technical challenges which remain unresolved for PLS in VLC research, including PLS coding, massive MIMO, non-orthogonal multiple access, full duplex technology and so on. Moreover, it is not possible to employ conventional PLS techniques as in RF communications [2]. In fact, the most practical communication scheme for VLC systems is intensity modulation and direct detection. Due to the nature of light, the intensity-modulating data signal must satisfy a positive-valued amplitude constraint. The state of the art, the challenges, and future works of the PLS enhancement methods for VLC are presented in this paper.

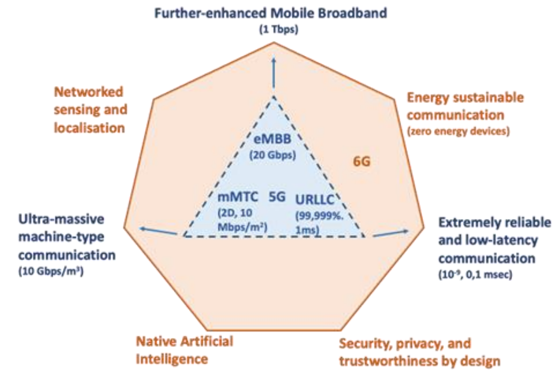

Fig. 1. 6G classes of services.

STATE OF THE ART

PLS will play a vital role in enhancing cyber-security in wireless networks. Moreover, it will also help reduce both the latency and the complexity of novel security standards. The provision of user security is distributed across all layers of the open systems interconnect (OSI) model. The integrity and confidentiality of information is typically ensured by using secret and public key encryption methods. However, the strength of these techniques may be enhanced by reducing the attack surface. In this regard, the PHY exposes significant vulnerabilities due to the broadcast nature of the wireless channel. PLS systems can leverage the challenges presented by wireless channels, such as fading and noise, to enhance secrecy. By utilizing the randomness inherent in the channel, PLS ensures that messages remain concealed from adversarial users. It is well known that if the eavesdropper is equipped with sufficient computational power, protocol security cannot guarantee the secure transmission of information.

PLS is based on a strong theoretical basis, which has been established at least five decades ago. In more detail, the mathematical framework for wiretap channels was introduced by Wyner in 1975, eliminating the need for a secret key to guarantee secrecy. Subsequently, in 1978, Csiszar and Korner demonstrated the existence of channel codes that can provide both robust transmission and secrecy simultaneously. Also, in 1978, Leung-Yan-Cheong et al. introduced the concept of secrecy capacity. The main advantage of using OWC technology for increasing PLS is that light does not propagate through opaque objects such as walls. Light beams are also very directional – think of a laser beam in the extreme case. Hence, light beams can be formed without the need for excessive signal processing efforts. Lenses and other optical components can be used to shape a beam. It is, therefore, possible to significantly reduce the possibilities of man-in-middle attacks in LiFi compared to WiFi. Fundamentals and techniques of PLS, developed for RF channels involving wire-tap coding, multi-antenna, relay-cooperation, and PHY authentication, cannot be applied directly to VLC channels. This is mainly because many standard specifications in transmission protocols and modulation schemes of VLC systems are quite different from RF systems. Besides, light can easily be confined spatially and, since there is no fading because the wavelength is significantly smaller than the size of the detector, the VLC channels become more deterministic.

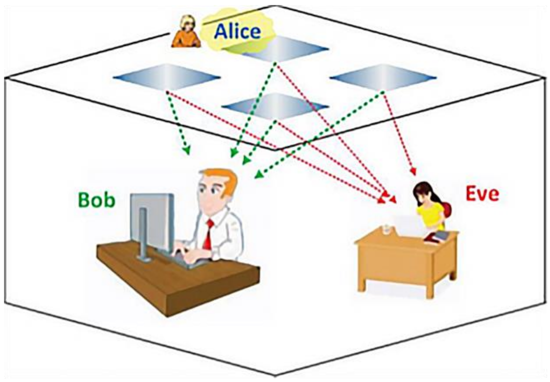

Fig. 2. An indoor SISO PLS scenario.

State of the art PLS techniques are mostly based on techniques such as jamming, mapping of transmitted symbols, precoding, and subset selection, as well as combinations of these techniques. A typical indoor single-input-single-output (SISO) PLS system is shown in Fig. 2. In addition, MIMO and wavelength division multiplexing (WDM) can be employed to enhance PLS. In this context, SM exhibits advantageous features due to its property to use the propagation channel for information transmission. In SM, the information is carried by the transmitted symbols, as well as by the indices of an active transmit unit. MIMO and MIMO-SM-based PLS systems were studied extensively in research and development work widely presented in the literature [3]. However, it is important to note that practical systems may be unaware of potential interceptions by passive eavesdroppers. Consequently, sub-optimal secure MIMO transmission is primarily achieved through Tx preprocessing techniques such as precoding, friendly jamming, mapping, and selection.

In precoding approaches, widely adopted in most applications due to their simplicity, through the channel state information at the Tx of the legitimate user, the precoding matrix coefficients are constructed through some optimization techniques so that the confidential message is perceived by the legitimate user clearly while the eavesdropper's bit error rate performance is degraded substantially. On the other hand, friendly jamming is based on the transmission of a signal that creates an artificial noise, which lies in the null space of the legitimate user. After combining the confidential information with the jamming signal at the Tx side, only the eavesdropper will experience destructive effects from the jamming signal. In the secrecy enhancement techniques, the secrecy is realized by an encryption key for the given modulation. The same key is used on the legitimate user's side to decode the confidential message. Another PLS enhancement technique, called Tx subset selection, is based on choosing a specific subset of transmitting entities according to the radiation patterns of the transmitting units.

The design of confidential signal sets is based on maximizing the minimum Euclidean distance or SNR at the legitimate user. Finally, the hybrid design of VLC and RF systems was expected to improve the user experience, substantially, since VLC systems can support reliable high data rates in specific areas and RF systems can provide coverage when a LoS link is not available. They can co-exist, operating in the same environment, without causing any interference. It is also possible that both systems share the same PHY techniques and medium access control (MAC) algorithms such as authentication and encryption. A Tx luminaire communicates with the legitimate Rxs in the presence of an external eavesdropper, which can be combined for hybrid RF/Optical PLS systems [4]. Since hybrid VLC/RF systems have both VLC and RF components altogether in the system, PLS for such systems should be jointly investigated due to the broadcast nature of both technologies. In more detail, to increase PLS in cross-band VL/RF systems, a joint resource allocation is needed, considering all the available resources and corresponding constraints, the overall CSI information and the users' quality-of-service requirements. For example, if a user requires a high level of PLS and is located near an LED access point (AP), the system's resource management system may avoid using RF to serve this specific user.

CHALLENGES AND FUTURE WORKS

VLC is a technology that will boost the emergence of next generation wireless networks. However, despite the inherent advantages of this technology regarding some specific features, e.g., security, compared to the RF counterpart technologies, the related weaknesses should be further investigated and mitigated. More specifically, the use of VLC does not imply the immunity of the communication system to security threats, due to the broadcast nature of VLC systems. Thus, further enhancing PLS in VLC systems can make VLC one of the core technologies for 6G applications that require a high level of cyber-security. Using some metrics such as the secrecy rates, the secrecy performance of VLC system can be significantly improved in various scenarios through well designed PLS techniques. A promising approach is based on the design of novel algorithms for PLS in multiuser and broadband VLC systems. To this direction, the use of new modulation schemes such as SM techniques, including index modulation and OFDM-index modulation, and optical multiple-input-multiple output techniques with non-orthogonal multiple is very promising. The algorithms to be designed must have high power efficiency and must have the capability to work in multi-user scenarios. In particular, the artificial jamming signal generation property of these modulation techniques is the most important advantage in providing PLS compared to the traditional approaches.

Also, the successful use of VLC to increase PLS in future generations of wireless networks depends on two issues: a) the successful collaboration of this technology with the prominent RF communication systems, and b) the potential to use visible light technology in a multi-fold way to simultaneously offer several functionalities, including secure communication, lighting, sensing and localization, and power transfer. Such an approach could have a major impact on several important real-world applications, including smart industry, distributed and cloud computing, extended reality, etc. In more detail, except the cross-band resource allocation that has been discussed in the previous section, another promising approach to increase PLS in cross-band VL/RF systems is by using VLC to increase the sensing and localization precision. This approach can directly improve security and trustworthiness since the physical location of each node is known. Also, the information acquired from sensing and localization can be used to optimize the beam steering in the RF-based MIMO subsystem. To this direction, the use of machine learning has shown important advantages compared to conventional optimization techniques. Another promising research direction is the investigation of PLS in cross-band systems with simultaneous lightwave and power transfer (SLPT) [5]. For example, the jamming signals can be used both to increase the secrecy rate and for energy harvesting by IoT devices, which in the uplink can report their data to the AP by using RF.

Consequently, the main research challenges for PLS in VLC are as follows:

- Which are the most suitable PHY features to be exploited for the definition of security algorithms in 6G heterogeneous environments characterized by high network scalability and different forms of active malicious attacks?
- How can PLS and covert communication be provided in a proactive way and without requiring feedback from the wireless devices?
- How can PLS be provided for devices with extremely low energy consumption (e.g., IoT) or zero-energy devices and how can it be combined with other key technologies for the seamless operation of the aforementioned devices, e.g., SLPT?
- Which MAC protocols for VLC offer notable advantages in terms of PLS and which of them are suitable in different VLC applications?
- How much can the use of reconfigurable optical lenses (e.g., at the Rx) and intelligent surfaces improve PLS?
- How can artificial intelligence be exploited to tune PLS algorithms dynamically?
- How can lightweight key distribution and authorization techniques best be developed that leverage the previously obscured PHY-layer attributes while maintaining ultra-low latency (ULL) quality of service (QoS)?
- How can lightweight key distribution and authorization techniques best be developed that leverage the previously obscured PHY-layer attributes while maintaining ULL QoS?

- What relevant, unique dimension reduction/feature extraction methods could enable transfer learning while maintaining the privacy of aggregator networks over various RF interfaces?
- How can PLS be ensured with Txs (i.e., LED APs) and PD-based Rxs distributed in different locations?
- How can confidentiality be ensured between the central baseband processing unit and antenna stripes?
- How can user mobility and device orientation be incorporated into the VLC channel models and combining VLC and RF?

ACKNOWLEDGMENTS

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OPTICAL CAMERA COMMUNICATIONS

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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. In addition, estimating 3D pose of objects is desirable in many applications including human-robot interaction, manufacturing automation, intelligent transportation systems (i.e., autonomous vehicles, vehicles/drones platooning, etc.

VLC employing LEDs as Txs and complementary metal-oxide-semiconductor ISs (or cameras) as Rxs is best known as **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 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 Rx 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].

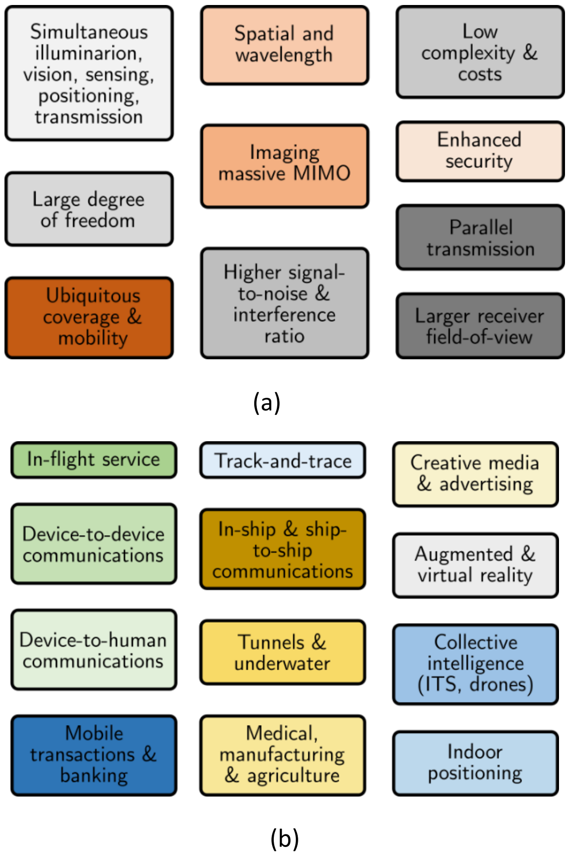

Fig. 1. VLC-OCC: (a) key features, and (b) typical applications.

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 MAC modifications.

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 Rx 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 SNR and, consequently, higher bit error rates (BERs). 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., OOK, FSK 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 SM, multilevel intensity modulation, distance colour-coded OOK [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 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.

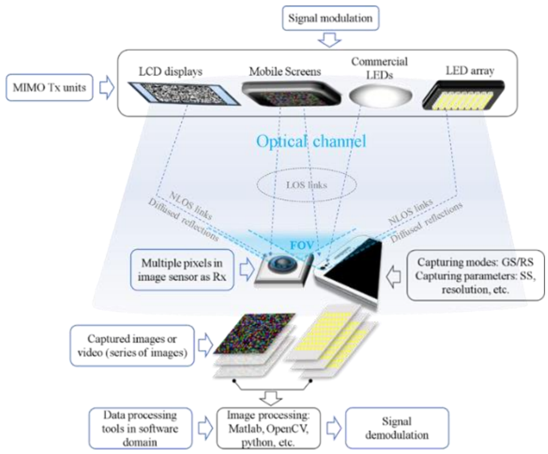

Fig. 2. MIMO-OCC.

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 PD Rxs, which do not truly represent the IS-based Rx. 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.
- *Capturing a small size light source in RS*-based camera – The scan rate is faster than the frame rate is slower than the scanning rate by several rows vertically aligned. Therefore, portions of vertically aligned rows not capturing a light source have no contribution to captured data signal.
- *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 Tx and Rx 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 Rx is within the field of view of the Tx. 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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PRACTICAL IMPLEMENTATION OF OUTDOOR OPTICAL CAMERA COMMUNICATION SYSTEMS WITH SIMULTANEOUS VIDEO AND DATA ACQUISITION

V. Matus, J. Rabadán, and R. Perez-Jimenez

INTRODUCTION

The utilization of **VLC** systems, such as Li-Fi, which offer simultaneous illumination and data transmission using LEDs, has primarily been confined to indoor applications where link spans are short and the interference caused by background lights is manageable. Outdoor implementations of VLC are not feasible due to the high intensity of sunlight and the need for longer link spans. However, **OCC** allows for intrinsic source and noise segregation using existing camera equipment, albeit at lower speeds [1].

In outdoor environments, OCC brings promise in supporting data reception for sensor networks, a use case that often requires low data rates, a large number of nodes, and a restricted energy budget. Furthermore, OCC systems can offer simultaneous video and data acquisition, a significant advantage in scenarios such as surveillance systems, as depicted in Fig. 1, where variables from a farming field, such as soil moisture, humidity, temperature, and others, can be monitored by sensors that transmit data using LEDs to a surveillance camera or a drone monitor. The dual data and video acquisition functionality is possible when certain conditions are met: the dimensions of the LED-based source at the Tx side are small, the linkspan is long, and the camera field of view is wide. In these conditions, the LED's projection on the IS is of negligible area, leaving most of the image free for video monitoring.

Our study examines the novel sub-pixel OCC condition, which occurs when the Tx size is less than the size of a pixel at the image plane. When the sub-pixel condition is satisfied, most of the information from the Tx is captured by one single pixel, with adjacent pixels receiving an attenuated copy of the information due to camera de-focus or atmospheric scattering and turbulence.

STATE OF THE ART

Since early implementations of OCC, most systems have exploited the effect of rolling-shutter (RS) acquisition in which the IS of the camera is exposed on a row-by-row basis [2], significantly improving the achievable data rate at the expense of the field of view and link span, leaving no room for the actual image or video capture during the communication process. In turn, global-shutter (GS) systems have been long neglected due to the scarcity of such type of IS, which has mainly been replaced by more cost-effective **complementary metal-oxide semiconductor (CMOS)-based sensors**.

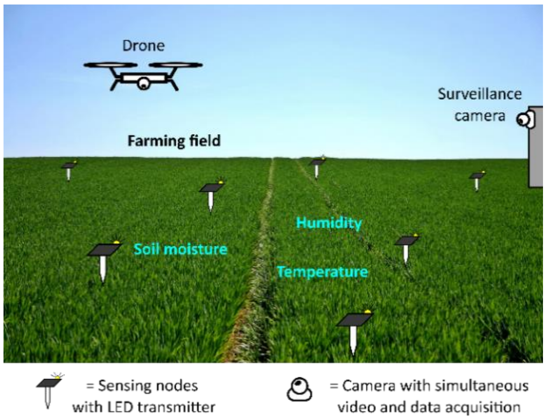

Fig. 1. Use case of optical camera communications allowing simultaneous video and data acquisition from LED-enabled sensing nodes in a farming field.

The inherent capacity of cameras to separate multiple sources of light has been exploited to implement multiple-Tx topologies, taking advantage of spatial division and MIMO techniques [4]. Using the camera as a multiple-PD Rx, it becomes possible to simultaneously transmit independent data streams from multiple Txs, each associated with a different LED source. The camera can spatially divide and capture the individual signals, enabling parallel communication channels and increasing the system's throughput.

Outdoor OCC systems face challenging atmospheric conditions that degrade the link, such as turbulence, particles in the air, sunlight, and different types of precipitations. Nevertheless, thanks to the image-forming optics and the control over the photographic parameters of the camera, it has been demonstrated that such conditions can be efficiently overcome [5].

By combining the previously mentioned sub-pixel conditions, we have demonstrated that an OOK signal can be transmitted at distances in the range of one hundred meters. In Fig. 2, we show the signal obtained by a single pixel in these conditions. As can be seen in the image, the setup allows for simultaneous video and data acquisition, promising a practical way to implement sensor networks based on sub-pixel OCC.

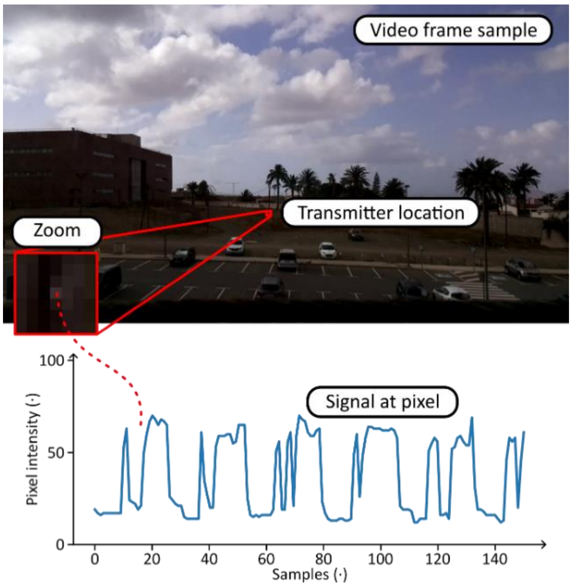

Fig. 2. Signal obtained from video footage in outdoor OCC with subpixel conditions

CHALLENGES AND FUTURE WORKS

The main challenges in the implementation of sensor networks using OCC in outdoor environments are the energy budget for the Tx and the discovery and tracking of nodes. LED Txs can be energy efficient if oriented correctly with a narrow beam, but this limits the mobility of the nodes. On the other hand, mobile nodes would require high-power LEDs with isotropic radiation patterns, thus consuming more energy. Additionally, from the image processing perspective, the receiving nodes need to identify multiple nodes in the video stream and track them over time if they are moving. This requires adapting artificial intelligence-based computer vision models, trained for pattern recognition, to recognize and interpret the unique patterns created by the communication process.

Future works need to focus on developing efficient Txs that can adjust the radiation pattern of the light source. The data rates and energy efficiency could also be enhanced by using M-ary PAM schemes. At the Rx, the development of image processing algorithms needs to address pattern recognition, tracking, and image stabilization, combined with digital signal processing for the demodulation of the information. Cloud-based architectures should also be explored since the processing of heavy computer vision models can be delegated to a back-end instead of the computing module of the Rx. The protocols for video streaming and compression should be taken into account in the data detection process.

Furthermore, the extrapolation of subpixel OCC to short-range links holds the potential for supporting sensor networks in indoor facilities. The available LED indicators in most devices and machinery meet the subpixel condition for standard cameras at a few meters distance. This opens new opportunities for applications such as indoor localization, smart home and office automation, and wearable devices, where subpixel OCC can provide efficient communication and monitoring capabilities.

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VISIBLE LIGHT COMMUNICATIONS FOR INTELLIGENT TRANSPORTATION SYSTEMS

Murat Uysal

INTRODUCTION

Intelligent transportation systems (ITSs) are built upon cooperation, connectivity, and automation of vehicles, and are expected to improve the safety, efficiency, and sustainability of passengers and freight while enhancing the comfort of driving. The practical implementation of ITSs requires highly reliable, robust, and scalable **vehicle-to-everything (V2X)** communication solutions enabling **vehicle-to-infrastructure (V2I)** and **vehicle-to-vehicle (V2V)** connectivity. The information gathered via V2X communications provides the drivers with real-time information on traffic and road conditions including collisions, congestion, surface condition, traffic signal violations, emergency brakes, etc. Furthermore, such information can be used by the local transportation departments to develop traffic efficiency applications, e.g., platooning, or by automotive manufacturers to develop safety applications, e.g., collision avoidance. Besides these road safety functionalities, potential in-vehicle applications have recently emerged such as high-speed internet access, multiplayer gaming, cooperative downloading, and mobile commerce because of ever-increasing dependency on the Internet and multimedia services.

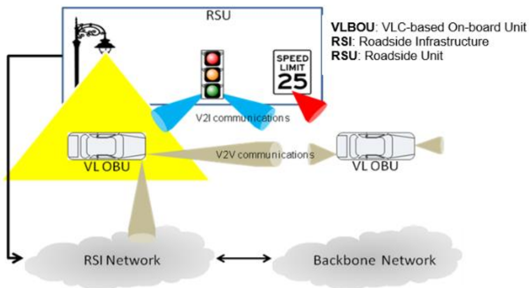

Fig. 1. Vehicular VLC network.

Research efforts and standardization activities on V2X have been so far centred around RF technologies. In 2010, as an amendment of the IEEE 802.11 WiFi standard, IEEE 802.11p standard was introduced to support V2X communications in the 5.9 GHz band allocated for ITS applications. In 2017, a cellular-based V2V connectivity solution, known as LTE-V, was introduced as a part of 3GPP Release 14. Since the current market penetration of V2X solutions is relatively low, the allocated RF bands are considered sufficient at the time. However, soon, high interference levels can be experienced in limited RF bands, particularly in high-density traffic scenarios. Channel congestion will result in longer delays and degrade the packet rate. To address such issues, VLC has been proposed as an alternative vehicular access solution to RF-based V2X communications [1]. VLC takes advantage of widely available LEDs and utilizes them as wireless Txs in addition to their primary illumination function. Since automotive manufacturers are increasingly using LED-based exterior lighting, front and back vehicle lights can serve as wireless Txs making VLC a natural vehicular connectivity solution.

VLC-based V2X: Basic Concept and Advantages

As illustrated in Fig. 1, a vehicular VLC network consists of onboard units (OBUs), i.e., vehicles, and roadside units (RSU), i.e., traffic lights, street lamps, digital signage etc. Additionally, RSUs are connected to the backbone network via the road side infrastructure (RSI) network. Vehicles fitted with LED-based front and back lights can communicate with each other and with the RSUs through the VLC technology. Furthermore, LED-based RSUs can be used for both signaling and broadcasting safety-related information to vehicles on the road.

In comparison to RF counterparts, VLC offers inherent advantages such as immunity to the electromagnetic interference, operation in unlicensed bands, inherent security, and a high degree of spatial confinement allowing a high reuse factor. VLC is well-positioned to address both the low latency required in safety functionalities (i.e., emergency electronic brake lights, intersection collision warning, in-vehicle signage, platooning) and high speeds required in so-called infotainment applications (i.e., map downloads and updates, media downloading, point of interest notification, media downloading, high-speed internet access, multiplayer gaming, etc). Furthermore, VLC is a cost-effective and green communication solution since the dual use of LED lighting systems on vehicles and the roadside infrastructure is targeted.

A LED-based VLC system would consume less energy compared to the RF technology, thus allowing the expansion of communication networks without added energy requirements, potentially contributing to the global carbon emissions reduction in the long run. VLC is also appealing for scenarios in which the use of RF band is restricted or banned due to the safety regulations, e.g., industrial parks such as in oil/gas/mining industries. VLC could be also used for positioning and navigation purposes. Although GPS is widely used today, it fails to provide sufficient accuracy in environments where there is no LoS path such as tunnels, indoor parking lots, and some urban canyons. For such cases, VLC-based positioning technology is more attractive.

STATE-OF-THE-ART

With attractive features and potential application areas discussed within the previous section, vehicular VLC has received increasing attention lately, see the recent surveys in [2] and [3]. The current literature can be roughly divided into two categories based on the type of receptor. A vehicular VLC system can deploy a PD or an IS (camera) to receive the optical signal transmitted by the LED-based head- and taillights. Since cameras are already deployed in most vehicles for safety applications such as parking assist and lane detection, these built-in cameras can be also potentially used for VLC systems. In such a camera-based VLC system, the received light from the imaging lens projected onto the IS is converted to binary data by the readout circuit. The IS consists of multiple micron- sized reception pixels. Based on the configuration of the readout circuit, ISs use either rolling shutter or GS technology. In the latter typically used with CCD IS, all pixels are read at once. In the RS technology typically preferred in CMOS ISs, pixels are read one row/column at a time, which makes them relatively faster in comparison to the GS. Nevertheless, their frame rate (typically 30–100 fps) results in a throughput of tens of bits per second limiting their application to mainly basic safety functionalities. The limitations of camera-based solutions have prompted researchers to explore the use of PDs to enable much higher data speeds in vehicular VLC systems. PIN (p-n diode) photodetectors are more favorable for vehicular VLC due to lower cost as well as better linearity performance and high-temperature tolerance. Despite a higher cost, APDs have higher sensitivity and provide better gain compared to PIN counterparts which make them a more robust solution, particularly in adverse weather conditions.

The current literature on vehicular VLC is well established in terms of channel modeling and PHY design. Different from indoor LEDs, the headlights and taillights exhibit asymmetrical intensity distribution. Considering such vehicular LED characteristics as well as weather conditions, channel models for vehicular VLC were developed and extensive simulation studies and analytical results were presented to demonstrate the fundamental limits of vehicular VLC systems, see e.g., [4]. While earlier works on vehicular VLC are limited to simple pulse modulation techniques and single-hop configurations, more recent works have demonstrated significant improvements via the use of more sophisticated PHYs such as optical OFDM and its variants. Optical OFDM was shown to be effective in handling the ISI resulting from multipath propagation and the limited bandwidth of LED. Multi-hop transmission techniques made it possible for the signal transmitted from the source vehicle to reach the destination vehicle through a number of intermediate vehicles (relays) eliminating the need for LoS requirements. Hybrid VLC/RF links were further proposed to ensure link availability under all weather conditions.

CHALLENGES AND FUTURE DIRECTIONS

While recent experimental works have already demonstrated the feasibility of the vehicular VLC, further research efforts are required in several areas of vehicular VLC before commercialization and widespread adoption of this promising technology. In particular, the dynamic conditions imposed by the outdoor medium (i.e., adverse weather, the effect of sunlight etc.) and vehicle mobility necessitate the design of adaptive transmission solutions. At the PHY, link adaptation might involve the selection of modulation type/size, channel code rate, and/or transmit power based on the instantaneously received signal-to-noise ratio. On the hardware level, the vehicular VLC system can be modified to enable dynamic adaptation of its Rx field-of-view (FOV) or use an adjustable optical attenuator to minimize the incoming background noise.

In order to transform vehicular VLC into a full-fledged solution, additional efforts in the upper layers are further required. For example, most of the MAC protocols in the literature assume isotropic radiation of RF systems. The fact that VLC systems with their inherent directionality render conventional schemes practically useless dictates the need for the design of novel MAC protocols that consider the directionality of the illumination pattern of headlights and taillights. Another critical research topic that requires further investigation is the integration and co-existence of vehicular VLC with RF-based technologies such as IEEE 802.11p and C-V2X. Initial experimental results have shown that such heterogeneous solutions can compensate for the drawbacks of each other and improve the overall performance. However, additional efforts are required for a full integration at the hardware level possibly exploiting the common system architecture based on OFDM.

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ON THE USE OF VISIBLE LIGHT COMMUNICATIONS IN INTELLIGENT TRANSPORT SYSTEMS: FROM ROAD VEHICLES TO TRAINS

Anna Maria Vegni

INTRODUCTION

Visible light communication technology is foreseen as a key technology in the context of next generation 6G wireless networks, mainly due to its spectral, energy, and cost efficiencies. VLC is expected to be adopted as a complementary technology for RF networks, especially in places where RF networks fail to support end-users with their quality-of-service requirements. Furthermore, VLC is a candidate as a green technology, providing communication enhancements due to high data rates, while guaranteeing illumination and security requirements.

The dual paradigm of providing both illumination and communications allows VLC to be suitable for several application scenarios, where lighting devices are used. Ranging from V2V and V2I communications to multi-user data offloading, as well as high-speed train communications, the use of VLC systems can be largely adopted in **intelligent transport systems**, mainly for safety and positioning applications. VLC has been initially identified to support safety applications in vehicular ad-hoc networks, considering packet transmission from a vehicle to the forwarding one, by means of multiple hop V2V modes. Also, the use of fixed nodes, like Rus, and the existing infrastructure, has allowed packet transmission according to V2I-I2V mode.

This paper presents a brief description of the use of VLC in ITS, in the case of different application domains, ranging from vehicular networks to railways, as presented in Section 2. In particular, VLC is envisioned as a promising technology in railway, due to the need of overcoming existing technology solutions that are becoming obsolete, such as the GSM-R standard. As of today, GSM-R is going to be substituted by novel solutions for managing wireless multi-bearer links for train-to-ground (and vice versa) available along the rail path, such as **future railway mobile communication system** and **adaptable communication system**. A short discussion about this aspect is finally provided at the end of this paper.

STATE OF THE ART

The main vehicle safety applications are identified by analyzing the occurring frequency and the impact of different classes of accidents. The most representative safety applications are summarized in Table I, showing the high-priority applications with very strict limits concerning the latencies [1], with values below 100 and 20 ms limits for the pre-crash sensing, and a maximum required communication range that varies between 50 and 300 m. Information about communication mode and message length are also provided. This points out that in vehicular applications, up to a certain limit, the connectivity, the robustness, and the latencies are prior to communication distances.

In ITS, VLC considers LEDs as transmitting devices and photodetector or image sensors as Rxs. In the latter case, image sensors are adopted in Optical Camera Communications, which represents a sub-class of OWC systems. In OCC systems for ITS applications, image sensors are mounted both on the taillights and on the front side of every vehicle. Each vehicle broadcasts its own ID and other information to neighboring vehicles. Images are captured and detected using deep learning techniques among the numerous interfering light sources on the road. In [2], the schematic of image capture from the LED taillights, by means of convolutional neural networks, is presented, to detect the distance between two neighboring vehicles.

In railway scenarios, VLC applicability mainly refers to data communications, and voice and video-streaming services. The deployment of VLC systems can be easily adopted, by replacing existing luminaries used for illumination on the trains with white LEDs. However, the applicability of VLC systems can be adopted not only on the train itself but also on station buildings, along trackside, inside tunnels, as well as in case of station/yard scenarios [3].

In the case of a mainline/highspeed scenario, where train speed can reach very high values, VLC systems can be exploited for data communications and signaling, related to the train operations. In [4], it was described as the signal passed at danger (SPAD) risk, which refers to the occurrence of a train crossing the stop signal without the authority to do so, thus causing accidents. SPAD can be caused by several factors, including driver's inattention, distraction, fatigue, incomplete route knowledge, misunderstanding, and poor sighting of trackside signals. In this situation, VLC can be applied to increase the efficiency of the current methods of avoiding SPADs, such as the ***automatic warning system and train protection & warning system***, by means of their integration. Specifically, the emitting lights of the trackside signal can be detected by the photodetectors laying on the train, and then the information will be decoded as a visual/ audio alert shown on the monitor of the train driver.

Table I. Classification of high-priority safety ITS (vehicular) applications, [1].

Application	Maximum range [m]	Maximum latency [ms]	Message length [bit]	Type
Traffic Signal Violation Warning	250	100	528	I2V
Curve Speed Warning	200	100	235	I2V
Emergency Electronic Brake Light	300	100	288	V2V
Pre-crash Sensing for	50	20	435	V2V

Cooperative Collision Mitigation				
Cooperative Forward Collision Warning	150	100	419	V2V
Left Turn Assistant	300	100	904, 208	I2V / V2I
Lane Change Warning	150	100	288	V2V
Stop Sign Movement Assistant	300	100	208, 416	V2V / I2V

CHALLENGES AND CONCLUSIONS

As emerged, the use of VLC systems in vehicular networks is consolidated, while more recently in railway applications it is largely increasing, also due to the pressing request for enhanced performance of new rail applications. H2020 AB4Rail project (https://www.ab4rail.eu/) aims to identify novel emerging technologies, eligible to replace GSM-R and allow new railway services and applications. It has been envisaged the usage of aerial and space technologies, such as high-altitude platforms (HAPs) and high-throughput LEO satellites, as well as optical wireless technologies like VLC and Free Space Optics. For each alternative bearer, different technological features and limitations are being investigated in AB4Rail project, and it is expected that the use of synergy among multiple bearers can be suitable to guarantee performance in different railway scenarios and applications.

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OPTICAL WIRELESS COMMUNICATIONS TECHNOLOGIES FOR SMART MANUFACTURING IN INDUSTRY 4.0

Beatriz Ortega and Vicenç Almenar

INTRODUCTION

Over the constant evolution of industries towards further improvements of efficiency and quality of the products, current industrial generation is commonly referred as Industry 4.0. In this paradigm, the connection of the production systems to a communication network, called cyber-physical system, becomes critical to allow industrial automation and smart manufacturing, where Software-Defined Cloud Manufacturing and augmented reality can be introduced into intelligent production systems.

5G communication networks provide reliable links with high capacity, low latency, and low jitter between machines, sensors, and computing systems but pioneering works are being conducted toward next-generation wireless networks. More concretely, the International Telecommunication Union (ITU-T) standardization sector launched a focus group called Technologies for Network 2030, which is expected to consider new potential use cases such as holographic-type communications, ubiquitous intelligence, tactile Internet, multi-sensor experience and digital twin in smart industrial environments, see Fig. 1 [1].

Fig. 1. Examples of use cases in future smart manufacturing (freepik.es).

6G new scenarios have been proposed from 5G ITU-R M.2083 definitions to meet the requirement of such use cases including **ubiquitous mobile broad-band** (uMBB), **ultra-reliable low-latency broadband communications** (ULBC) and **massive URLLC** [1]. Different applications including machine motion control, mobile robots or mobile cranes amongst others were listed by 3GPP TR 22.804 and TS 122.104 with corresponding requirements, which can be summarised as several Gbps data rates, high demand for reliability (> 99.99%) and low cycle times (tens of µs).

Such increase in transmission data rates, the density of connections, and latency requirements lead to spectrum exhaustion and traffic congestion which can be overcome by using higher radio frequencies (mmWave and even THz range) at the expense of limited reach. An attractive solution is provided by optical wireless networking which exploits 320 THz bandwidth in the visible light spectrum (400-700 nm) and/or 12.5 THz in the IR spectrum centered at 1550 nm and has been identified as the main enabler due to the robustness against the electromagnetic interference, availability of unregulated optical frequencies, high reliability, and high security (i.e., spatial confinement). Moreover, due to the aforementioned advantages, OWC is also proposed to integrate high-accuracy positioning systems which are also essential in industrial environments for smart manufacturing [2], as explained below.

STATE OF THE ART

However, the most significant limitation of OWC systems in smart factories is the blockage of the LoS (i.e., non-LoS), i.e., due to moving robots. Current solutions utilize relatively wide beams, antenna diversity or MIMO schemes. In [3] a distributed multiuser MIMO is proposed for industrial plants to cope with the problems associated with blockage situations. A dense network of optical frontends Txs coordinated by a unique access point (AP) allows to implement spatial diversity or spatial multiplexing and supports mobility along the hall as the AP dynamically selects the set of OFE that covers the user’s position. Several beam steering methods in OWC systems have been previously reported by using tunable MEMS and spatial light modulators (SLM) and, also, by using passive elements such as a pair of gratings for 2D steering or an arrayed waveguide grating router. In [4] narrow 2D steered IR beams were proposed to be employed in Industry 4.0 to create separate and close links to each device where a matrix of PDs allows the deployment of a wide field of view Rx to facilitate the alignment in smart factories.

Moreover, other approaches are based on the concept of intelligent reconfigurable reflecting surfaces and the use of diffuse reflection focusing on beam reconfiguration has been recently proposed in order to simplify the indoor environments of Industry 4.0. In this system, the light beam is reflected in a small area with waveform shaping based on a SLM, focused, and steered to the desired user by using a transfer matrix control algorithm in a centralized unit. The use of a centralized LED with no intermediate electro-optical conversion stages for optical fiber-wireless links has been also recently proposed in factory networks.

BMW or Wieland Electric are examples of pioneer companies where LiFi technology has been successfully employed in production lines although further improvements are required before full deployment while ongoing joint research projects between companies and academia continue to explore the potential of VLC/LiFi systems in an industrial environment towards reliable, low latency and secure wireless communication for future Industry 4.0 scenarios.

LOCALIZATION IN INDUSTRIAL ENVIRONMENTS

Smart manufacturing systems in Industry 4.0 will require precise location information to be able to know the positions of production resources (i.e., tools, robots, products, workers, etc.) and to deploy ITS within the factory environments. For the outdoor environment, the global positioning system is widely used as a navigation system. However, its use inside buildings is limited by the severe attenuation suffered by RF signals from satellites. For indoor localization, there are localization techniques based on Wi-Fi, but the obtained accuracy is rather limited because of the complex multi-path propagation of radio waves. Ultra-wideband radio is an alternative as these systems can obtain high accuracy, but high-cost implementation limits its application in manufacturing plants.

CHALLENGES AND FUTURE DIRECTIONS

OWC is a promising alternative to RF-based indoor localization, moreover, it can be combined with illumination when visible light is used for communications. The main advantages of this solution are (*i*) can be easily deployed in buildings; (*ii*) makes use of an unlicensed spectrum; (*iii*) multi-path has a negligible impact; and (*iv*) avoids interference into other rooms. There are two main alternatives to implementing OWC indoor localization: either based on optical camera communications or based on Li-Fi communications [2]. The first approach uses illumination fixtures to transmit a unique low rate (few kHz) beacon signal which can be captured by a camera to identify its localization, this information can be combined with the angle of arrival estimation. The Li-Fi alternative makes use of the standard G.9991 PHY frame structure to implement time-of-flight measurements to estimate the position of the Rx, it requires the Rx to have access to at least 3 Tx units and gives higher accuracy than the first approach.

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OPTICAL WIRELESS COMMUNICATION BASED SMART OCEAN SENSOR NETWORKS FOR ENVIRONMENTAL MONITORING

Ikenna Chinazaekpere Ijeh

INTRODUCTION

The demand for advanced technologies to monitor, analyze, and manage the world's oceans has led to the development of smart oceans. Smart oceans of the future will involve the development of interconnected applications through the underwater internet of things [1]. This will involve the use of smart sensing technologies such as buoys or autonomous ocean sensors, unmanned underwater vehicles for remote monitoring and data collection, and the use of machine learning for predictive modeling and forecasting, among other advancements.

The oceanic environment is increasingly vulnerable to climate change and pollution, such as gas flaring in some coastal regions of Nigeria with large oil and gas deposits. This activity generates greenhouse gases and harmful pollutants that endanger human health, marine life, and the environment. To tackle these challenges, efficient monitoring of oceans is crucial, allowing for reliable impact assessment and proposing effective mitigation or adaptation strategies. An environmentally friendly and reliable underwater communication technology is therefore required to facilitate continuous data collection and transfer from smart ocean sensor networks. Among the available options, wireless communication is the most preferable due to its flexibility, cost-effectiveness, and low environmental impacts. **Optical wireless communication** is a most promising technology for high-speed data transmission, allowing for real-time monitoring over short-to-moderate ranges with low power consumption [2, 3].

Some environmental monitoring applications of OWC in ***smart ocean sensor networks*** include tracking changes in an ocean's temperature, salinity, dissolved oxygen, and pH levels. Other applications include monitoring carbon sequestration efforts, offshore oil and gas platforms, water quality for aquaculture operations, and early signs of natural disasters such as tsunamis or environmental threats like oil spills, to enable an effective response.

CONCEPT OF OWC BASED SMART OCEAN

Fig. 1(a) shows a smart ocean sensor network for environmental monitoring, where an OWC link is used for data transfer between an autonomous underwater vehicle (AUV) and an underwater sensor node. Subsequently, the AUV can either transmit the data directly to a sea surface platform or go afloat, for the onwards transmission to a satellite. Thus, making data available for control stations to analyze and make decisions. A practical application scenario is shown in Figure 1b, where optical modem modules from UON Technologies are attached to both an underwater infrastructure and remote operated drone for monitoring and data collection [4].

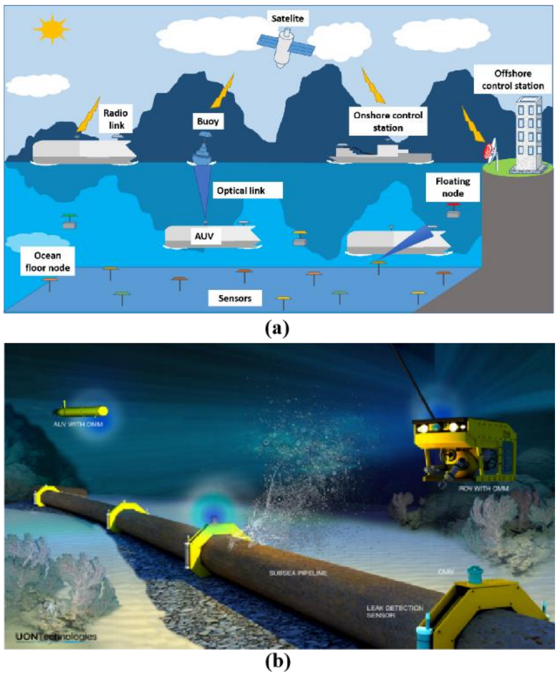

Fig. 1. (a) Illustration of OWC used in a smart ocean sensor network for data retrieval and transmission, and (b) An optical modem module deployed in monitoring underwater pipelines (reproduced from [4] with reference therein).

System architecture

The smart ocean architecture could comprise of a 5-layer system —which accounts for both the underwater and above-water environment, see Fig. 2 [1]. It consists of sensing, communication, networking, fusion and application layers. In the underwater environment, the sensing layer provides identification and sensing of data using both sensors and cameras. Thereafter, the communication layer handles the data transmission via a suitable communication technology (e.g. radio, acoustic, magnetic induction, optical) based on the application demand. The network layer utilizes the underwater to above water communication channel, which may involve direct or multi-hop links, to transfer data from sensor nodes and sensing devices hosted by AUVs, buoys, or other sea surface platforms to the fusion layer.

Above the water surface, the fusion layer uses cloud and edge servers to process large amounts of received data using fog and cloud computing technology. Lastly, the application layer, based on the processed data from the fusion layer, provide secured smart services for use cases such as ocean monitoring and exploration, underwater robotics, port security, etc. [1].

Underwater OWC system

Several organizations are committed to promoting sustainable ocean development through advanced ocean technology, and among them is the SFI Smart Ocean. Their primary focus lies in the development of autonomous and smart underwater wireless sensor networks. In the bid for efficient data exploration, the test cases of the SFI Smart Ocean pilot demonstrator included the deployment of underwater acoustic monitoring system to collect data transmitted from a rig by modems, cNODE and W-Sense. However, acoustic, and even RF technologies are not capable of meeting the growing demands for high data rate and low latency underwater transmissions over a considerable link range with minimum energy requirement, all which OWC offers, see Table I.

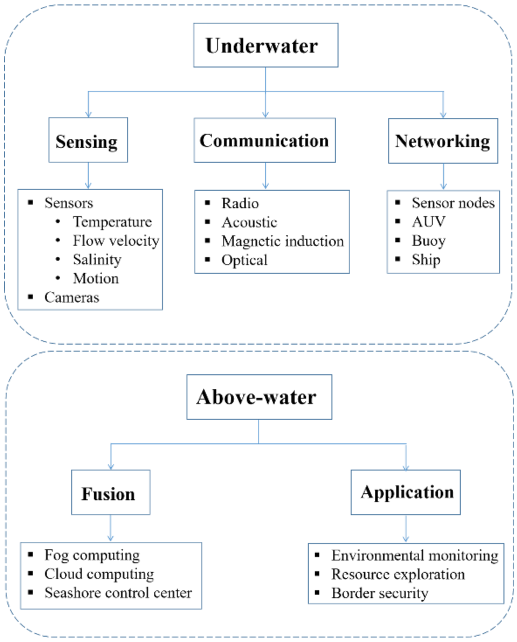

Fig. 2. System architecture of a smart ocean (inspired from [1]).

There are UOWC systems (consisting of a Tx light source and a Rx photodetector) available commercially or as prototypes, suitable for various use cases. For example, Shimadzu Corporation recently developed MC500 UOWC modem, which using green and blue laser light source can achieve data rates up to 20 Mbps over a range of 80 m. Another optical modem called the LUMA X from Hydromea can achieve up to 10 Mbps across more than 40 m, while the BlueComm 200 (made up of light-emitting diodes and photomultiplier tube) from Sonardyne can operate up to 150 m and achieve a data rate of 10 Mbps. Their UV counterparts, LUMA X-UV and BlueComm 200 UV, still maintaining same data rates operates at ranges of up to 30 and 75 m respectively. These UV series make use of an ultra-violet light source, hence are resilient to the presence of other light sources.

On the other hand, prior to commercialization, some UOWC system prototypes have been developed and tested. MIT researchers developed the AquaOptical modem, which could transmit Mbps of data over a few meters. An improved version, AquaOptical II, achieved higher transmission ranges and data rates. Ifremer, Institut Fresnel research lab and Osean SAS Co. developed an optical modem based on the highly sensitive silicon photomultiplier. For internet applications, the Aqua-Fi, a portable, low-cost and energy efficient UOWC system was showcased in a laboratory setup (see [4] and references therein).

Table I. Comparison of underwater wireless communication technologies (reproduced from [4] and reference therein).

Features	RF	Acoustic	Optical
Data rate	hundreds of kbps	kbps	hundreds of Mbps
Band-width	MHz	100 kHz	150 MHz
Latency	High	Moderate	Low
Range	up to 10 m	hundreds of kms	up to 100 m
Transmit power	up to hundreds of Watts	tens of Watts	few Watts

STATE OF THE ART

Recent studies on the UOWC technology are focused on improving its various aspects to make it more reliable, efficient, and cost-effective. Energy efficiency is crucial to increase the lifetime of the network. Low-power light sources and transmission protocols can be used to optimize energy consumption. Another option could be the use of sensor nodes to harvest energy from ambient underwater sources [2]. Some other considered areas include [2-5]:

Channel characterization:

Accurately characterizing the underwater optical channel is important for optimizing UOWC system performance. Techniques such as empirical measurements, theoretical models, and simulations are used to study these channels. Water turbidity, scattering, absorption, and turbulence can negatively impact the propagating light signals. There is currently a focus on accurate modeling of vertical transmissions as parameters such as temperature and salinity vary significantly in vertical links compared to horizontal links and can impact system performance.

Transceiver components

Advanced technologies for LED-based UOWC systems include power-efficient blue LEDs with phosphor conversion layers, UV LED sources, and pressure-neutral resin casting for small and light optical transceivers. However, converted green or amber LEDs result in reduced bandwidth, and UV LEDs trades off reduced impact of solar radiation to increased water absorption. Micro LED arrays and quantum-dot LEDs require further development before being used in commercial UOWC systems. Photodetectors suitable for low-light high-speed applications include photomultiplier tubes and silicon photomultiplier, but they can be affected by solar radiations. For higher light levels in shallow waters and short ranges, positive-intrinsic-negative PDs and avalanche PDs are suitable. Single-color LEDs with large active areas can also serve as PDs for low-cost applications in special cases.

Noise

Experimental testing of optical underwater communication is often done in darkened laboratories to avoid interference from ambient sunlight that can affect system performance. Optical bandpass filters are commonly used to reduce sunlight interference, but a newer approach is to use a liquid crystal display as a dynamic optical filter or adaptive optical aperture to mitigate ambient light and even interference in multi-user scenarios.

Hybrid communications

Adopting RF communication in the underwater environment especially in seawater is very limited due to its high conductivity which increases the attenuation of the propagating electromagnetic wave hence limiting link range and achievable data rate. The conventional hybrid approach for underwater communication is the optical-acoustic system setup. For instance, UOWC is used for high data rate near-range inter-AUV communication and acoustics are used for signaling events between sensor nodes or exchanging mission objectives with mission control. However, a promising and less explored area is the combination of magneto-inductive (MI) communication with UOWC. UOWC is suitable for visibly clear water scenarios and relatively unaffected by changes in salinity, but its performance deteriorates in turbid waters. On the other hand, MI is less sensitive to water turbidity but experiences significant signal attenuation in high salinity waters.

Localization

UOWC localization schemes can be categorized into distributed and centralized schemes. In distributed schemes, every underwater optical sensor node localizes itself by communicating with multiple anchor nodes using time of arrival and received signal strength (RSS) based localization techniques. In centralized schemes, the location information is sent periodically to the underwater optical sensor nodes by a surface buoy or sink node. Only the RSS technique has been known to be applied in centralized schemes. Commercial UOWC localization systems include Bluecomm from Sonardyne and Anglerfish from STM.

CHALLENGES AND FUTURE WORK

Data transmission via the UOWC link is challenging and depends on several factors majorly related to the aquatic channel and the practical constraints. For instance, the link range is limited by signal attenuation due to beam absorption and scattering, as well as by oceanic turbulence. In the absence of efficient localization schemes, misalignment of UOWC transceivers possibly due to ocean currents and waves will affect the link reliability. Also, solar radiations or even lights from underwater vehicles can affect the transmission quality. In addition, the limited energy capacity of the underwater sensors or devices constraints the optical transmit power and hence, limits link range and data rate.

Several research directions are necessary to tackle the challenges hindering the widespread deployment of UOWC systems. An important aspect for consideration is the underwater-to-above water communications as it ensures the accessibility of data for ease of processing and analysis. This could entail direct or relay points from water-to-air mediums with UOWC to same or mixed communication links, such as UOWC-to-terrestrial OWC or UOWC-to-RF, exploiting either the high data rate of OWC links or the easy omni-directionality and long-range transmission capability of the RF link. Relevant research in this area would involve the development of efficient relay and physical-layer security schemes.

In the underwater environment, it is important to conduct adequate investigation and accurate modeling of the UOWC channel to propose effective solutions for mitigating signal intensity degradation, particularly for vertical links, as there have been limited studies in this area. Multi-hop transmission through the use of AUV swarms and floating sensor nodes as relays could increase link range and enable energy transfer.

Furthermore, the effective and uninterrupted functioning of the increasing number of sensors can only be achieved through the implementation of wireless power transfer technology. Localization, especially for node tracking in the dynamic underwater environment, is a critical aspect of UOWC systems. It is important to consider the impact of transmission quality, range, and energy on localization performance. Moreover, it is necessary to shift considerable focus towards higher layer aspects of UOWC systems, such as developing efficient routing protocols and network architectures to enhance connectivity and coverage [2, 5]. Lastly, the use of artificial intelligence should be explored to develop intelligent and self-learning functionality for smart ocean sensor networks in the constantly changing underwater environment.

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UNMANNED AERIAL VEHICLES WITH LIGHTWAVE TECHNOLOGY FOR 6G NETWORKS

Panagiotis D. Diamantoulakis, Vasilis K. Papanikolaou, and George K. Karagiannidis

INTRODUCTION

The integration of terrestrial and aerial networks is one of the key objectives of wireless networks beyond the fifth generation (5G). Toward this direction, the **unmanned aerial vehicles** are envisioned to be used as part of the network's infrastructure for coverage extension, traffic offloading in crowded environments, and rapid recovery of the network services in cases of emergency. More specifically, the use of UAVs as ad-hoc mobile base stations can have several important real-world applications, such as vehicular networks and train backhauling, building/human health monitoring, precision agriculture, the interconnection of critical infrastructure such as smart grids in a secure way, and virtual reality. Also, UAVs can be utilized as mobile edge servers in order to support functionalities such as mobile edge computing and federated learning, with the potential to reduce delay and improve privacy. The latter is of paramount importance for 6G networks, which can be seen as the superposition of communication and computing networks, in which distributed nodes are able to support artificial intelligence applications [1].

In the integration of UAVs and ground networks, energy efficiency, cost, and ease of deployment need to be considered, which also constitute important challenges toward the 6G networks. The effective use of UAVs depends on the communication performance and the UAVs' flight time duration. The bottleneck of the communication performance is usually imposed by the front hauling link, i.e., the ground-to-air (G2A) link. On the other hand, the flight time of the UAVs is limited by their battery capacity, while, in the general case, the UAVs' power consumption is composed of the propulsion power, the communication-related power, e.g., for the communication between the UAVs and the users via the air-to-ground (A2G) links, and the power consumption for data processing. To address the aforementioned challenges, the use of hybrid OWC/RF technology is particularly promising.

The Concept of Energy Autonomous UAV-based Communications Systems with SLIPT

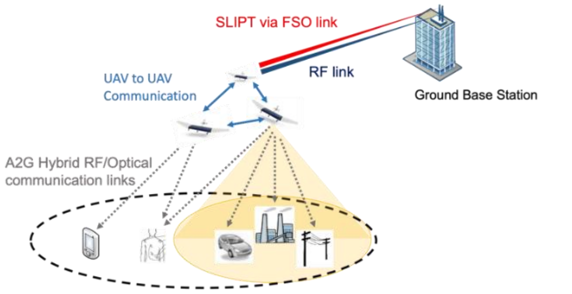

Fig. 1. Cooperative air-to-ground and ground-to-air hybrid RF/optical system with SLIPT.

In Fig. 1, the reference architecture of a multi-UAV cooperative G2A-A2G network is illustrated. In the proposed setup, multiple UAVs are used to serve multiple users in an ad-hoc way. To mitigate the front hauling bottleneck, a dedicated FSO link can be used for the communication between the ground base station and the UAVs, as rates up to 80Gbps have been reported in the literature for FSO G2A communications, while in order to further increase the data rates and especially reliability, an RF link, e.g., mmWave, can be used in a complementary way. The communication between the UAVs and the users can also be based on hybrid RF/OWC technology, while the directivity of the corresponding OWC links depends on the use case.

For example, FSO may be the best option for the point-to-point communication between UAVs and smart grids infrastructure, while VLC or IR-based broadcasting technology can be utilized for the information transmission between UAVs and multiple vehicles. Also, when using the RF technology, except for increased reliability and throughput when used in parallel with the OWC links, it is necessary to retain connectivity with conventional mobile users and IoT sensors. Furthermore, RF can be used for the exchange of control signals among UAVs, which can collaborate to perform swarm operations. Finally, in order to meet the energy requirements of the UAVs and extend their flight lifetime, energy can be transferred via the dedicated FSO link by using the SLIPT technology.

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As it has been proposed in [2], SLIPT can be implemented by equipping UAVs with solar panels. In this regard, by using lightwave power transfer, flight time has been shown to be increased up to 24 times, while other reports showcase a 200W power transfer for a distance up to 100m. To explore the potential of using SLIPT as an enabler of energy-autonomous UAV-based networks, relevant research attempts have mainly focused on three different directions, namely the optimization of SLIPT, channel modelling, and the investigation of the impact of network topology on the achieved performance. In more detail, the use of SLIPT creates an interesting trade-off between the harvested energy and communication performance of the FSO link, calling for the optimization of the resources, e.g., optical power and time, that are allocated to energy transfer and information transmission [2]. However, although the analysis in [2] provides the optimal configuration with respect to the instantaneous channel gains, to characterize the long-term performance of UAV-based FSO systems, appropriate theoretical channel models are needed.

Conventional FSO channel models are not applicable in UAV-based communications, which is mainly due to the UAVs’ mobility and the random fluctuations of UAVs’ position and orientation because of the dynamic wind load, and random air fluctuations in the atmosphere around the UAVs, and the internal vibrations of the UAVs. Thus, the incident laser beam is in the general case non-orthogonal to the Rx plane, while the fluctuations may be correlated [2]. To this end, theoretical models for the geometrical and misalignment losses caused by the random fluctuation of the position and orientation of the UAVs have been proposed in [3]. Also, in practice, the flight time of UAVs is interdependent on the network’s topology and consistency, which can be modelled by using stochastic geometry-based tools [4].

CHALLENGES & FUTURE RESEARCH DIRECTIONS

A. Experimental Channel Modelling

As it has already been mentioned, the precise statistical modelling of channel is of paramount importance for the quantification of the stability requirements of UAVs in order to maintain a certain link quality, which is determined by the communication quality-of-service requirements, as well as the required amount of harvested energy when the G2A FSO link is used for SLIPT. However, to fully address the aforementioned issues, experimental results are needed, as well as the matching of the statistical parameters with the UAVs’ specifications. Similarly, another challenging issue is the statistical modelling of the VLC/IR G2A links.

B. Cross-layer Optimization

For the design, orchestration, and resource allocation of UAV-based networks of Fig. 1, several different parameters need to be jointly optimized, such as the size and weight of the UAVs, the capacity of the batteries, the size of the information buffers, the transceivers design and the photodetector's light collecting area, the UAVs trajectory or placement, the utilized PHY and MAC layers techniques, the tracking system, the handover mechanism, the data-processing requirements, etc. In addition, the use of multiple frequency bands has the potential to increase the data rates, but it also increases complexity and, thus, the corresponding energy consumption. These considerations create several interesting trade-offs that require cross-layer optimization approaches. The formulated problems may be particularly challenging, making the use of model-free machine learning methods in order to solve them a promising alternative.

C. Quantum Key Distribution through UAVs

One of the most promising uses of UAV-enabled FSO communications is to increase communication security in critical applications. Current security protocols are limited by their public use of unsecured communication channels and as such, they are vulnerable to computational and hardware advancements. To address that, quantum communications (QC), that are facilitated through the reliable transmission of quantum states, have given rise to QKD. QKD offers superior efficiency in securing key distribution by capitalizing on the laws of quantum mechanics while it has already been implemented in both fiber optic networks and through free space optics for terrestrial and aerial links.

However, in optical fibers, path loss scales exponentially with distance, whereas in atmospheric links, such as UAV-to-ground links, the main cause of loss is diffraction, which scales quadratically with distance. This condition makes FSO through aerial platforms a prime candidate to implement QKD. There are two main ways that QKD can be implemented. The most common is to encode the information onto a quantum state of a single photon, such as phase or polarization. Although single-photon Rxs can be developed, they are costly and highly cumbersome to be maintained on a UAV. On the other hand, more recently, the continuous variable QKD has been implemented by encoding the key onto the continuous quantum variables. The main challenge for FSO QKD is that accurate channel modeling for atmospheric QC links is required since weather effects and pointing errors due to misalignment and jitter can severely inhibit the transmission.

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VIRTUAL REALITY

Olivier Bouchet

STATE OF THE ART

Currently, there are two major players in the VR HMD market (Oculus, HTC) and two entrants (PiMax and Varjo). Oculus and HTC propose both tethered and untethered HMDs, untethered ones being able to embed computing (Oculus Go, Oculus Quest, HTC Vive Focus), or use wireless communication between the graphic server and the headset (HTC Vive Cosmos with a Vive wireless adapter). We have seen the development of Inside-out tracking solutions that do no longer need external to track the headset and its controllers. This inside-out tracking solution can theoretically make them mobile in a boundless space but they are unfortunately still tethered and rely on a computer for processing power.

A problem posed by tethered HMDs is the actual tether. Tethered HMDs require to be plugged into a computer in order to work. To address this problem, some companies like MSI or HP build VR backpacks that allow the players to carry the computer on their backs while running through the simulation. Wireless VR is even more important for user comfort considering not only the weight of the backpacks, but also the freedom of movement required by the convoluted custom stages built by LBE VR companies to maximize user immersion.

To address this problem, companies like TPCast provide external modules that can be plugged into the computer and the HMD to allow wireless video and audio transmission with extremely low latency [1]. The TPCast boasts latency under 2 ms and uses a proprietary wireless protocol in the 60GHz band range for a data bandwidth of 7 Gbps. However, the problem with TPCast and other similar solutions is that they can only be used for one user at a time because it is impossible to get multiplex the signals on the 60 GHz band.

There are currently three different classes of HMDs with varying screen resolutions: the *mass market* HMDs such as the Oculus Quest, the Oculus Rift S, the HTC Vive Cosmos, the HTC Vive Focus are currently at 1440 x 1600 (or 1440 x 1700) per eye; *high-end mono panel* HMDs, such as the PiMax 8K with a resolution of 2560 x 1440 (with an upscaling on the screen with a perceived resolution of 3840 x 2160) pixels per eye; and the *high-end multi-panels* HMDS such as the Varjo VR-2 where the perceived image is optically composed with two panels, one for the central field of view (1920 x 1080), and a second one for the peripheral field of view 1440 x 1600), see Fig. 1. HMD screen resolution is and will remain a major factor in the VR market competition and we believe the resolution will keep increasing with each generation until we reach the optimal resolution of 9000 x 7800 pixels per eye, which is the theoretical perfect resolution.

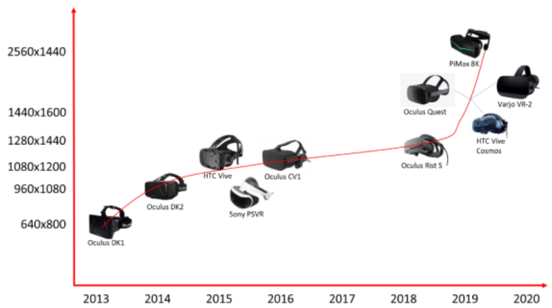

Fig. 1. Evolution of HMD resolution

Indeed, the growth of display resolutions raises the issue of real-time rendering, directly dependent on-screen resolution: the higher the display resolution, the longer the rendering takes. Besides increasing resolution, another barrier to fully immersive free-roaming VR is the restrained area in which a user can move. In the context of tethered HMDs, the largest area in which a user can currently be tracked is 4x4 meters using the HTC Vive lighthouse tracking system. It is possible to build custom solutions using the independent tracking systems developed for CAVE-like systems (such as ART or OptiTrack) but they must be custom built and custom software developed and externally integrated with existing systems.

VR AND OPTICAL WIRELESS SOLUTION

Virtual Reality is quickly becoming a fast growing market and the technology is fast evolving. In order to accommodate the growing market of multiuser VR, untethered VR is mandatory. But growing resolutions and graphics performance to enhance immersion of the end user means that more and more computer power will be needed to simulate realistic VR worlds in ultra-high resolutions of 9000x7800 pixels per eye in HDR. Furthermore, the low photon to motion latency required to avoid motion sickness implies that zero latency compression is needed to transmit the video data, resulting in the need for extremely high bandwidth needs.

At its most ideal resolution a bandwidth of 470 Gbps is needed per user in the case of uncompressed video, while zero latency encoding can bring it down to around 120 Gbps par user. The KPIs shown in Table I recaps the different bandwidth requirements for optimal wireless multiuser VR.

Table I. KPI and estimated requirements for wireless multiuser VR in 2021.

Name	**Requirement**		
	Mass market VR	**High end VR**	**Prototype VR**
Potential HMD	HTC Vive Cosmos / Oculus Quest	Pimax 8K	N/A
Resolution	2 × 1440 × 1700	2x3840×2160 (2×4K)	2×7280×4320 (2×8K)
Bits per pixel	24	30 (HDR)	30 (HDR)
Frequency	90 Hz	120 Hz	120 Hz
Connection density	10 users / 100 m²		

DL Data Rate per user	9.8 Gbps	55.62 Gbps	210.88 Gbps
DL traffic density	98.5 Gbps / 100 m²	556.2 Gbps / 100 m²	2.06 Tbps / 100 m²
Low latency video compressio n bandwidth for 10 users (4:1)	24 Gbps	139 Gbps	527.2 Gbps
Video stream latency	< 2 ms	< 2 ms	< 2 ms

This clearly shows the need for wireless Tbps or Tbit/s connections and beyond in order to allow the spread and growth of multiuser VR applications. To achieve this target and in the context of WORTECS (Wireless Optical / Radio TErabit CommunicationS) European collaborative project [2], Orange Labs demonstrated in the University of Southampton's Optoelectronics Research Centre and in partnership with Oxford University, the possibility of wireless optical communication at 1.16 Tbit/s [3]. Using an optical medium of ten 100 Gbit/s wavelengths, the demonstration was able to achieve an aggregated rate of 1 Tbit/s (1000 Gbit/s) in both directions in an enclosed space. Irrespective of the world record, this wireless system offers photonic data speeds of 1 Gbit/s to 1 Tbit/s.

To proceed in a room, take a light beam from an AP optical fiber and automatically direct it towards the user terminal, then proceed reciprocally in order to obtain ultra-high speed communication in both directions. These Fi-Wi terminals include a light concentrator and a location and guidance unit for the beam so that it can follow the user's movement. This enables a direct connection between two optical fibers, with no need to transform the optical signal into an electrical signal (or vice versa), and no need for the signal processing and regeneration required for the radio alternative. Fi-Wi connections are intrinsically bidirectional, transparent to modulation type, to protocol and to wavelength, with a speed of 1 Gbit/s to 1 Tbit/s (theoretical maximum currently assessed at 44.2 Tbit/s), without modification to access point or user terminal. Data transmission is highly secured with a very closely directed light beam.

Electricity consumption is low and connectivity benefits from guaranteed speeds for each user since this is point-to-point communication. So Fi-Wi is a technological breakthrough, linking the fiber optics network directly to terminals. The solution creates an opportunity for an end-to-end optical network that uses fiber and remains wireless. Research in the field is generating increasing interest, and one of the next steps will be to go further with innovative applications, particularly in multi-user mode.

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OPTICAL NEURAL NETWORKS EMPLOYING VISIBLE LIGHT COMMUNICATIONS TECHNOLOGY

Mircea Hulea, George-Iulian Uleru, Othman-Isam Younus, Zabih Ghassemlooy, and Sujan Rajbhandari

INTRODUCTION

Typically, spiking neurons (SNs) model the key characteristics of the neural cells, which are used for information processing, as well as storage of synaptic weights and adaptability which implies changing of the synaptic weights in real-time. Note, "spikes" represent the emergence of action potentials initiated in neurons. Communications between SNs is usually established using discrete pulses that can be converted into optical pulses. The intensity of the postsynaptic response depends on the energy carried by the pulses set by the weights. Implementing these SNs with optical outputs in the analogue hardware domain enables parallel transmission of multiple colors (i.e., WDM) between neurons.

In order to deal with large quantities of data, traditional central processing units (CPUs) have almost reached their limits in the realm of data processing and machine learning. Existing artificial neural networks (ANN) have high processing times and energy consumptions, which are not desirable in many applications including smart devices. One of the main drawbacks of ANN is the requirement of the CPU to operate, which leads to slower processing. These issues can be resolved, to an extent, by switching to the optical domain offering large computational resources, excellent tuning capability and massive integrations using nan-photonic and nano-photonics. Thus, an optical neural network (ONN), where mathematical operations is performed on the input signal prior to being passed through several layers. ONN can be reailised in free space or integrated. The latter is more appealing since there is no need for high-accurate alignment, but the integration dimension is in a scale of maybe a dozen units per layer in contrast to thousands in the free space.

ONN architectures such as complex-calued ONN, multi-layer optical Fourier NN and coherent nanophotonic circuit have been investigated offering a number of features including (*i*) the low computational power of the neuromorphic hardware; (*ii*) high processing speed, rapid decision-making and energy efficiency (i.e., a single photon per e.g., 10^6 operations); (iii) multiplexing (*iv*) uses the license-free optical spectrum bands (i.e., UV, visible and IR bands); and (*v*) lower crosstalk and immunity to the radio-frequency induced electromagnetic interference, see Fig. 1 [1]. In addition, photonics can ease the trade-off between bandwidth and interconnectivity, which is the case in electronic-based connections [2]. These advantages make ONN suitable for high-speed brain inspired computing representing a faster and smaller alternative to the electronic SNN. Typical applications of ONN are focused on machine learning acceleration, nonlinear programming and intelligent signal processing. In addition, photonics is suitable for optical communications at very high rates because since transmission and processing are performed in the optical domain [2].

Fig. 1. The advantages of optical neural networks.

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Based on the implementation, the ONNs can be split into two categories of all-optical and electro-optical NNs. The former includes the photonic NNs, which offer high-speed and can be integrated on-chip [3], whereas the latter use electronic and optical components within the neuron's structure and are suitable for free space transmission. The photonic technology was first introduced in hybrid feed-forward NNs but afterwards, significant research activities focussed on the implementation of optical communications between different types of optical spiking neurons. Since 2014, when the first all-optical SNN was integrated into silicon, we have seen a growing number of research activities on implementations of all-optical synapses with spiking output. Considering that, adaptability is a critical feature of NNs, one of the main challenges of the optical synapses is to model using the physical laws of the learning rules of the biological synapses.

The methods for implementation of adaptive synapses in ONN include electro-absorption modulators, organic photosensitive materials, ZNO_{1-x}/ALO_Y heterojunction, and photoconductive materials such as graphene with carbon nanotubes, amorphous oxide semiconductors, and carbon nanotube field-effect transistors. The adaptive optical synapses can use even organic photosensitive material (PSM) in an application where the PSM produces the contraction of artificial muscles in response to the light intensity [3].

In NNs, the role of synapses is to transmit weighted signals to the postsynaptic neurons (*posts*). In early models of electro-optical neurons (EON) for non-spiking computational NNs, the weights are transmitted using *light intensity modulation* (LIM). This concept was adopted later in significantly faster photonic neural networks (PNN) using the silicon photonic weight banks [4]. In advanced PNN, the processing of the photonic spikes is performed using ultrafast laser neurons, where adjustable *weights* are implemented using different types of tunable silicon micro-ring resonators [5].

Note, in LIM-based ONN the transmission of the optical signal over several layers significantly reduces the intensity of the postsynaptic response. However, a solution to mitigate this problem is to amplify the optical signal. Similarly, in free-space-based ONN, the weighted signal is affected by the light intensity fluctuations during propagation, which depends on the transmission span.

Optical axons and applications in robotics - One possible option to mitigate the effect of intensity variation is to use the optical axon (OA) that eliminates the need for transmitting weighted optical signals (i.e., reduced implementation complexity of online learning mechanisms) and improves ONN's tolerance to the variation of light intensity [6]. As illustrated in Fig. 2, the OA connects the input module of spiking neurons with the electronic synapses.

For humanoid robots with SNN-based control units, the sensors on the limbs are neuromorphic and generate patterns of impulses. Taking into account that the limbs are in relative motion with the robot's body includes the MCU, the neuromorphic sensors (NS) are at varying distances from the main SNN. In such distributed SNNs with moving NSs, **VLC** can be used to enable communication and leverage visible wavelengths to transmit simultaneously information between neurons. However, hand movements introduce challenges for optical transmission such as channel alignment and variations in signal strength. These can be determined by varying channel length and angle of arrival that induces intensity fluctuations in the received optical signal. Due to their tolerance to the dynamic optical signal variation at the Rx [6], OAs can integrate bidirectional VLC to connect the neural MCU with the neuromorphic sensors (receptors) and with the neural drivers of the actuators (effectors) [7].

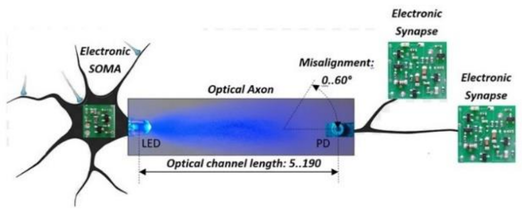

Fig. 2. The graphical representation of the optical axon in an electro-optical neuron.

The use of light-emitting-diode (LED)-based VLC in humanoid robots is justifiable due to the short link distance, typically less than 2 m, which aligns with the average height of humans. Typically, a robotic hand controlled by SNN incorporates a significant number of sensors. This implies that a fully connected hand employing VLC would require dozens of parallel channels to establish connections between the sensors and the main SNN. To solve this problem, VLC/OWC offers several solutions to increase the number of parallel connections based on the spatial distribution of the optical signals. As depicted in Fig. 3, there are several methods including (*i*) SLM and Fresnel lenses or photoelectric multiplication in homodyne detectors can be used to obtain the weighted sum of the laser signals generated by a significant number of neurons; and (*ii*) using diffractive optical elements for spatial multiplexing of several channels. Thus, multiplexing a large number of connections in ONN is primarily based on the spatial distribution of optical channels, which is easier to implement in directed point-to-point links.

However, all these techniques are proposed and evaluated for fixed point-to-point links, i.e. the studies do not consider the relative motion between the Tx (Tx) and the Rx, which affects the synaptic transmission due to signal fading. WDM in VLC can be utilized to achieve a parallel data transmission in ONN that tolerates the relative motion of neural areas [7]. However, the requirement of multiple narrow-band Txs and Rxs with narrow-band optical bandpass filters leads to higher costs and complexity, hindering widespread adoption. To overcome this challenge, low-cost solutions such as filter-less WDM were explored for WDM-VLC systems or multiple sets of independent weighted non-return to zero on and off keying data streams are transmitted at different wavelengths. At the RX, the aggregated signal is decoded by leveraging the varying responsivity of the PD for different wavelengths. The combination of responsivity and LED characteristics is utilized to realize a WDM-MIMO (multiple-input-multiple-output) system for achieving parallel data transmission.

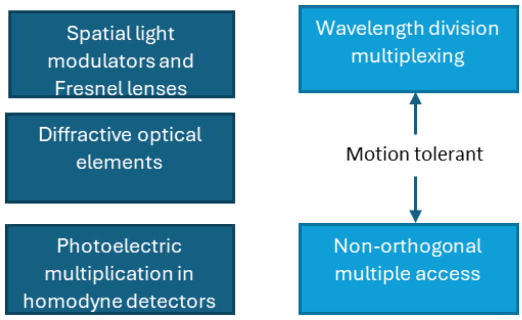

Fig. 3. Several multiplexing techniques for optical signals for point-to-point links (blue), and motion tolerant (magenta).

A multiplexing method in electro-optical neural networks uses non-orthogonal multiple access (NOMA) with pulse amplitude multiplexing (PAM) for the implementation of communication of the MCU with the sensors and effectors. Thus, instead of WDM, the signals generated by OAs are multiplexed by the amplitudes of optical pulses. For the implementation of the motion tolerance, an additional reference channel is used to dynamically adjust the optical Rx's gain. The results demonstrated that the influence of the proposed OA on the regulatory performance of the SNN depends on the physical displacement of the OR relative to the Tx. However, this influence of PAM-based OA did not affect the ability of the robotic arm to hold the object when OPL and deviation are limited [1].

CHALLENGES AND FUTURE WORKS

Note that neuromorphic electronics has a major limitation of interconnect density, which limits the neuromorphic processing speed and the associated application space to within the MHz regime. The photonic integrated circuits have become a promising platform for implementing fast and energy-efficient processing units, which can increase the performance of conventional digital signal processors due to the high speed of optical frequencies and low propagation losses of nano-photonic interconnects. The principle of weight encoding by spike amplitude has been implemented recently in a neuromorphic photonic system, where neurons are *ultra-fast and low-cost spiking vertical cavity surface emitting laser* (VCSEL) devices and the weight is implemented using *micro-ring resonators* that are highly efficient [8].

Neuromorphic engineering (NE) is the state-of-the-art fusion of neuroscience-based computing and photonic technology, which overcomes the constraints of conventional computing architecture, allowing high speeds with low latencies in the range of sub-nanoseconds, high bandwidth and low energy consumption, thus offering the potential of extending the domain of artificial intelligence. The advantage of the NE is in its capability to implement information processing by mimicking the human brain. The photonic neural networks were successfully integrated on-chip or implemented using the free space optical transmission technology. An important problem that needs resolving is the cost of photonic systems, which is significantly reduced by the new platforms [2]. The significant processing power of the PNN is useful for applications of artificial intelligence in medical diagnosis, telecommunications, and scientific computing [9].

In conclusion, the main advantage of PNN is the speed that is typically obtained by on-chip implementation. Secondly, the OWC represents an elegant alternative to hardwired connections in distributed electro-optical NNs.

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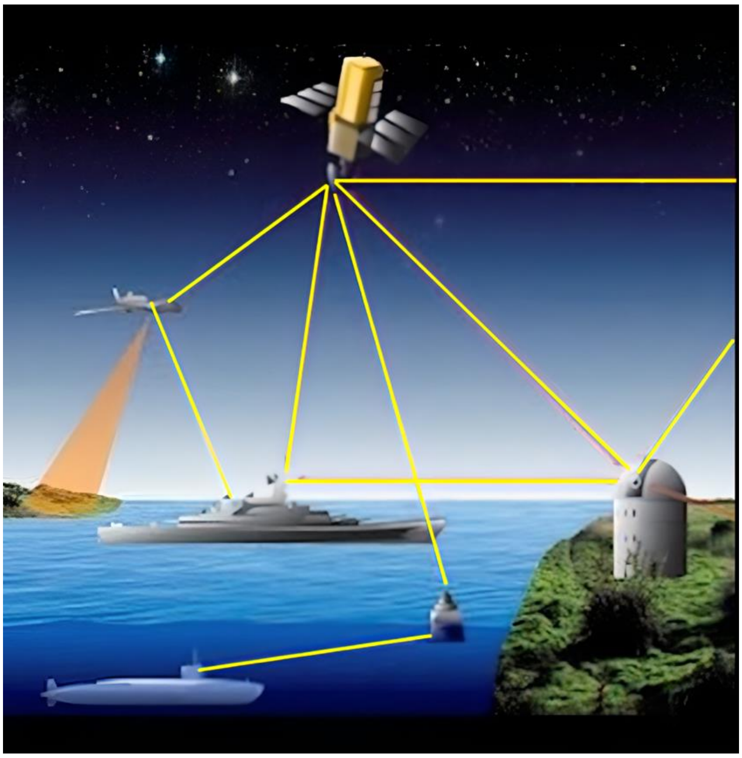
Medium-to-long Range Links



OPTICAL WIRELESS COMMUNICATION – MEDIUM TO LONG RANGE APPLICATIONS

Zabih Ghassemlooy, Mohammad-Ali Khalighi, Stanislav Zvanovec, Amita Shrestha, Beatriz Ortega, and Milica Petkovic

INTRODUCTION

It is imperative that the state-of-the-art data communication methods be used to meet the ever-increasing demand for higher data transfer bit rates at a lower cost and a lower energy consumption. The major challenges using RF technology are (*i*) costly spectrum licensing; (*ii*) congested spectrum, thus moving to higher spectrum bands i.e., higher millimetre wave (up to 100 GHz) and tera Hertz (0.1 – 10 THz), which however, are limited to link spans up to 100 m due to huge path loss and severe molecular absorption; and (*iii*) vulnerability to detection, interception and jamming. Therefore, in congested and contested environments (e.g., city centres, shopping malls, airports, stadiums, etc) using RF technology may result in a poor quality of service, lack of link availability, as well as providing opportunities for eavesdropping. In fact, the common approach in RF communication systems rely upon broadcasting data widely over a pre-determined frequency band and encrypting it to prevent interception.

In the last 50 years, the deployment of optical fibre technology has played a critical role in the growth of the Internet, network systems, cable television and telecommunications, thus transforming our lives and the world, providing very high data rates over long transmission distances, without cross-talk and with high quality and reliability [1]. However, in many cases, it is impossible or impractical to lay down fibre optic cables in rural and urban areas due to high costs. As part of global networks, optical wireless transmission systems (e.g., based on **OWC**) are the best option to complement both RF and optical fibre technologies, even though they are not intended to replace them. While civilian networks have been using RF, OWC, and hybrid RF-OWC technologies for several applications, they will continue to do so in the future. However, they are moving toward using **FSO** communication for a range of transmission range, data rates, and applications. FSO presents a new paradigm in communication systems as a complementary wireless technology to the RF-based systems. FSO systems typically transmit a narrow beam of light (i.e., a laser beam) between two specific points, effectively enabling a fibre optic cable in free space, and offering several interesting features as outlined in Fig. 1.

In recent years, the rapid developments and improvements in research laboratories and commercial telecommunication industry sectors have meant the components that are used in FSO systems to become smaller, compact, and more robust, thus enabling the users to bridge the technology into many diverse applications including space, terrestrial (i.e., access networks), and underwater. Every technological advancement in the last two decades, see Fig. 2, has helped make FSO communications more accessible, cheaper, faster, easier to deploy, and, ultimately, more commercially viable, as well as allowing operators to provide a bandwidth scalable system that can be used in the next generation FSO links. By merging FSO systems with the coherent technology in optical fibre communications together with adaptive optics, advanced coding/modulation and signal processing greater reach and higher capacity (i.e., tens of gigabits per second) than before can be achieved, enabling new applications in space and terrestrial links. According to Global Market estimates that the FSO sector is expected to grow from $4.4 billion in 2022 to $47.5 billion by 2027, i.e., a compound annual growth rate of about 34 % [2].

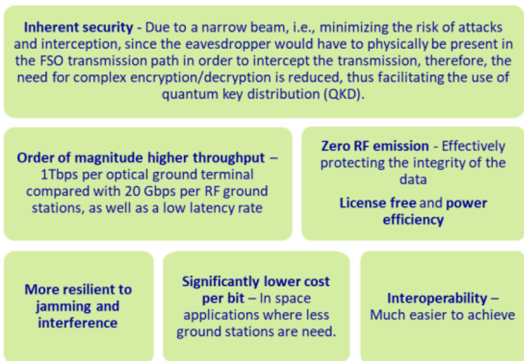


Fig. 1. FSO features.

FSO technology offering full duplex links with data rates of 100 Mbps to 10 Gbps and over 10 Gbps with auto-tracking and low latency (< 0.005 ms in some commercial systems, e.g., EL-10Gex from EC System) can be used in many applications including: deep-space, satellite, space-to-ground and ground-to-s[ace, terrestrial (the last mile access and cellular networks), smart environments, data centres, manufacturing, transportation, underwater, etc., see Fig. 3. The healthcare sector is one industry that stands to benefit greatly from FSO technology for medical equipment such as MRI machines and CT scanners. Few of the current key industry players in FSO communications are: Lightpointe Communication, Trimble Hungary, Wireless Excellence, fSONA Networks Corporation, Laser Light Communications, Plaintree Systems, Fog Optics, MostCom, SA Photonics, Inc., Centauri, Mynaric AG, Laser Optronics, Luma, Qinetiq, Anova Technologies, Optelix, EC Systems, and others.

(i) Space communications

Morgan Stanley's Space Team has estimated that $350 billion global space industry could rise to over $1 trillion by 2040, where 40 % of the space market will be dedicated to Internet services [3]. The evolving new space ecosystem includes Internet; earth observation; IoT; environmental monitoring; machine-to-machine communications; satellite-to-satellite communication; and data storage. In addition to technical advancements, the growing demand for bandwidth is also driving interest in FSO networks in space and terrestrial application since RF spectrums are congested and costly. It is becoming increasingly common for satellites to communicate via all optical links, whereas most ground-to-satellite communications use the traditional RF or microwave links. It should be noted that unlike the optical spectrum, which is licenced free, RF and microwave transmission bands requires licenses, thus leading to an increased interest in the use of high-speed (exceeding 100 Gbps) FSO systems for satellite-to-satellite, ground-to-satellite, satellite-to-high altitude platform (HAP) communications.

In addition, hybrid RF-FSO systems integrated into robust and highly scalable architectures may be used in back-haul and UAVs communications for providing expanded coverage areas and improved system performance [4]. In hybrid-based schemes we have the options of (*i*) FSO or RF link being used either for the downlink and/or uplink transmission; and (*ii*) using the RF link as a backup when the optical link experience link outage due to the combined effects of beam misalignment, channel conditions (i.e., turbulence, fog, etc.), and mobility.

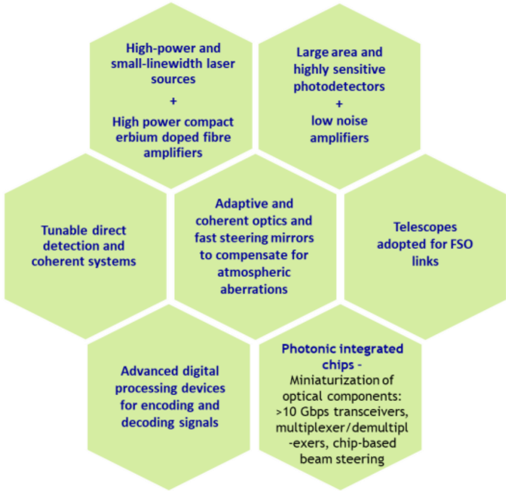


Fig. 2. Technological advances enabling widespread.

development of FSO systems.

Several companies intend to deploy mega constellations containing thousands of satellites in response to the global demand for global connectivity, which are connected through FSO links and are capable of exchanging data with each other nodes on the ground (e.g., UAVs, aircrafts, ships, and terminals), see Fig. 4. One of these satellites typically carries several optical communication terminals aimed at surrounding satellites in the same constellation. In addition to offering higher data transmission throughputs, these networks have built-in redundancy, which allows re-routing of the transmission path by bypassing malfunctioning satellites. Note that FSO-based satellite links require the laser beam from an Earth-based terminal to lock onto the satellite as it crosses the horizon, and then wait until the LoS path is established prior to transmitting the information data.

In addition, there are many UAVs (i.e., HAPs) to small drones, that could be used to in terrestrial communication systems with smaller coverage areas than satellite within in 5 and 6G and beyond in application such as providing (*i*) emergency networks for disaster areas; (*ii*) extending the wireless coverage to rural areas; and (*iii*) offloading ground terminal traffic in urban areas.

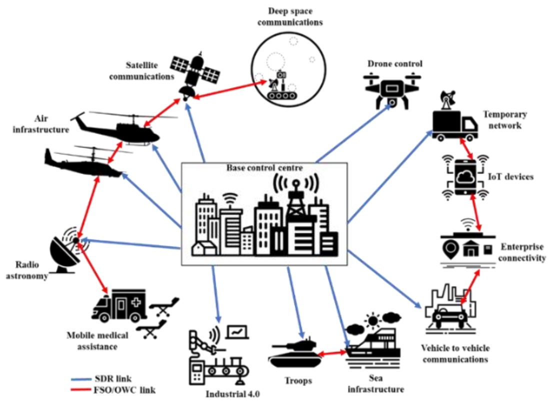


Fig. 3. Various potential FSO applications.

The optical feeder link between a ground station and a satellite enables a sustainable solution compared to RF technology allowing higher throughputs (e.g., 1 Tbps) at significantly lower cost/Mbps. Commercially, several satellite-to-ground links are still served with RF links, because of their low bandwidth, ease of installation, and lower cost over optical ground stations (OGS). In addition, RF offers higher availability links for users under clouds. The FSO technology can transmit encrypted data at higher rates by utilizing conventional WDM techniques, as well as lending itself well to quantum-based optical techniques, where single-photon-based optical sources and detectors can be used to encrypt information and ensure its secure transmission over long distances. Utilisation of QKD allows several advantages like network flexibility, and long-term security, though several impairments must be addressed [5].

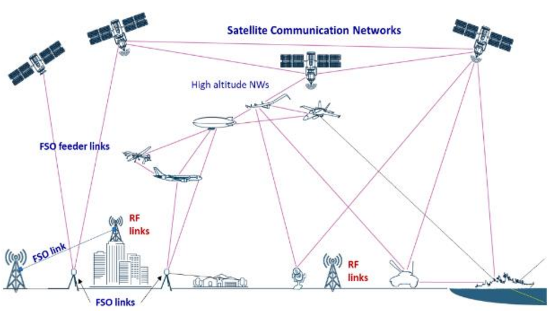


Fig. 4. Satellite communication networks.

The European Data Relay System (EDRS), a commercial partnership agreement between Airbus and the European Space Agency (ESA), was the first to report laser satellite communications at gigabit speeds. It is expected that as the demand for low-Earth-orbit constellations (LEOCs) increases, so will the demand for satellites, which, in turn, will lead to further optimization and commercialization of the necessary technology. Several LEOCs are currently being developed for launching in the mid-term, which will result in an increase in the number of FSO terminals in the orbit. These trends are being driven by organizations and initiatives such as the Telesat Lightspeed LEO Network (188 satellites), Rivada Space Networks (600 satellites), Rivada Space Networks (600 satellites), and Project Kuiper (3236 satellites), and SpaceX's Starlink (12,000 satellites, orbiting at an altitude of 550 km, with data rates of > 100 Mbps and an expected latency of less than 20 ms for ground terminals). The advantages of these FSO-based constellations over fixed, below-ground optical fibre communications links are that they are mobile and can be moved to wherever the need arises, such as during natural, or manmade, disasters, for example. However, common challenges for FSO links in space communications, ground-to-space, and space-to-ground communications are shown in Fig. 5.

(ii) Last meter and last miles terrestrial communications

The World Bank estimates that 80% of the population in developed countries have access to broadband high-speed internet compared to only 35% of the population in developing countries [6]. FSO communication offers the potential for better connection for groups that already have broadband internet access, as well as those that do not. As compared to RF wireless communication, optical communication provides bandwidth increases of 10 to 100 times. Due to labour and digging costs, the costs of setting up ground-based radio stations to receive FSO signals are also significantly lower than those associated with installing new optical fibre connections.

There is a limit to the speed and range of current microwave and RF technologies, i.e., beyond 10 Gbps data rates using microwave technology, and higher than 80 Gbps utilizing millimetre wave technology. Additionally, optical fibre deployments are not cost-effective for rural areas with a small number of customers. As the prices of key optical components continue to decrease, terrestrial FSO systems are becoming more competitive with fibre-based systems. In recent years, there has been a significant advancement in the optical transceiver technologies. It is anticipated that many FSO systems will be installed for use in terrestrial environment, which will contribute to further advancements in this area. In general, second-tier, or lower, operators are willing to adopt a new technology if it can increase the market share at a reduced total cost of ownership. Therefore, FSO can play a crucial role compared to alternative RF-based technologies. FSO-based networks rely on point-to-point or point-to-multi-point links between a Tx and single or multiple Rxs. However, when combined with local area networks and wireless local area networks the FSO links can provide very effective solutions to many scenarios as shown in Table I.

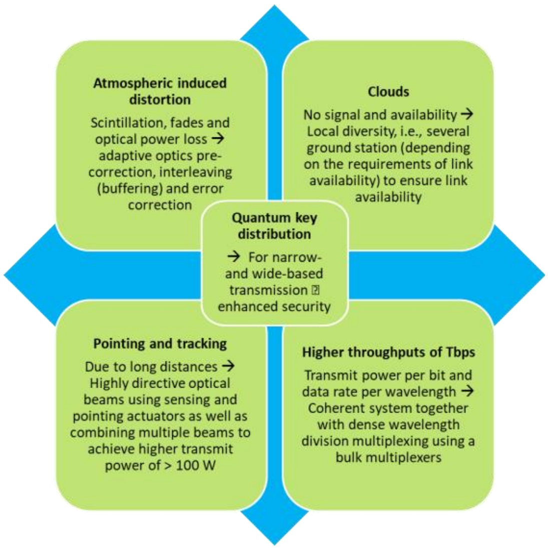


Fig. 5. Challenges in FSO.

It is also possible to deploy hybrid RF-FSO in this application scenario to always ensure link availability under all weather conditions. This can be achieved either by means of parallel transmission of RF and FSO signal or switching-over between them. Using hybrid THz-FSO technology can significantly improve the connectivity between small cells and the core network as well as overcoming the scarcity of bandwidth.

(iii) Underwater communications

Establishing underwater communications using wireless technologies eliminates the need to lay expensive fibres/coaxial cables across large distances to facilitate communication. There are distinct trade-offs between range and data rates in the underwater environment for all forms of communication technologies including (*i*) ***RF*** – Have a very limited transmission range, a limited data rate (i.e., 1 bit/Hz of the available bandwidth), and higher SNR requirements since RF signals are exponentially attenuated due to the high electrical conductivity of seawater [7]; (*ii*) ***acoustic*** – Have longer transmission range up to a few kilometres with a data rate typically on the order of tens of Kbps. However, they suffer from large latency (due to low propagation speed of acoustic waves), inter-symbol interference due to multiple acoustic reflections from the surface and bottom, and Doppler spread [8]. Additionally, acoustic communication is not suitable for seabed observations due to high security requirements; and (*iii*) ***optical*** – Have a range of data rates of few Mbps using LEDs, and potentially up to a few Gbps using laser diodes, thus enabling real-time video transmission for different applications including underwater vehicles and remote monitoring of underwater stations, etc., yet over moderated distances [9,10].

Since near-IR wavelengths are strongly absorbed by water, blue-green wavelengths are mostly used in underwater communications in conjunction with optical filters (to suppress ambient light). Unlike terrestrial FSO communications, underwater communication is mostly not impacted by turbulence. However, there are few drawbacks with FSO in underwater environments. The communication links are highly susceptible to (*i*) beam blocking (full or partial due to sediment deposits or passing undersea life); (*ii*) scintillation and beam wandering due to underwater currents and water bubbles; (*iii*) establishing direct LoS due to the uneven surface of the ocean floor; and (*iv*) absorption and scattering that limit the transmission range to a few hundred meters. Laser-based FSO systems are now available in the market include Sonardyne Bluecomm™ modems, Hydromea LUMA™ modems, and Shimadzu MC optical modems with different range, operation depth and the optical transmit power levels.

CHALLENGES AND FUTURE DEVELOPMENT OF FSO TECHNOLOGY

FSO systems are expected to experience improved performance and dependability due to advances made in component fabrication and device manufacturing, coding/modulations, signal processing, adaptive optics, beam steering, etc. The use of FSO technology in some applications may be limited due to the requirement for a clear line of sight between transmitting and receiving points as well as the associated cost. The space is poised to take-off and represent a significant new market opportunity for optical communications. Therefore, there are opportunities to leverage optical communication technology for space applications. The challenges in OWC including FSO and the future works are listed in Table II.

Table I. FSO for terrestrial application.

- A bridge between LAN-to-LAN connections in urban areas i.e., connecting enterprise buildings; and WLAN-to-WLAN connections - Hospitals, manufacturing sites, and campuses offering Fast Ethernet or Gbps Ethernet for many subscribers simultaneously
- Wireless services in rural areas, where there is no physical access to high-speed Internet
- High-speed links between the access and clint networks to backbone optical fibre core networks
- Converged Voice-Data-Connection
- Temporary WLAN network for events, emergency situations, etc.
- Back-up links in critical operations
- Plug and play for IOT with low power
- Distributed optical (laser) powering of IoT devices
- Optical sensing of physiological and behavioural traits

Table II. Challenges and future works.

1	***Hermetic packaging*** - The biggest barrier to implementation of FSO links is investment in space qualification, therefore, adopting hermetic packaging could speed up this process and help to address most of the environmental challenges.
2	***FSO with quantum encryption*** - The challenge of maintaining a communication link and combating atmospheric conditions while the Tx and the Rx move randomly needs addressing.
3	***FSO for IoT*** - The future of telecommunications will be shaped by the IoT, i.e., connecting and establishing data transmission between billions of devices, such as vehicles, smart devices, lighting fixtures, surveillance cameras, etc. In this scenario, OWC and specifically FSO technology will play a critical role, thus need more compact, less expensive, and low power devices.
4	***Standardization*** - 6G will require more bandwidth, which is a challenge that all currently used technologies must meet. FSO, therefore, plays a key role here, providing operators with an additional technology capable of handling the types of bandwidth that will be required in the backhaul network.
5	***FSO with high pointing accuracy and tracking*** - Which is several orders of magnitude more complex than in RF links. E.g., sub-microradian accuracy in deep space FSO links compared with the order of milliradians in the Ka band (30 GHz) RF links [11].
6	***Software-defined radio/optic and machine learning*** – For reconfiguring modules, predicting link performance, as well as switching between communication modes and sensing capabilities, thus offering unprecedented multi-functionality in wireless sensor networks.
7	***Single photon avalanche diodes technology*** - Improving the optical Rx sensitivity offering high detection, high accuracy, and high SNR.
8	***Space qualified photonic integrated systems (a single chip)*** – Incorporating low noise and high gain optical amplifiers, optical transceivers (> 10 Gbps), optical multiplexer/demultiplexers(ITU-grid DWDM 1.6 nm channel spacing); high power lasers (1 W or more with high stability), high power boosters (> 100 W) at the ground level; phase array and metamaterials; large area, high speed, and low noise photodetectors; coherent combining of multiple beams to combat turbulence; dynamic beam (allowing smaller lenses to be used at Rxs, i.e., beam shaping and beam focusing to concentrate the transmit power on target); and optical phase arrays.
9	***Aggregated multi-carrier*** - For space applications with flexibility at the optical level with optical switching for routing and optical bypass, etc.
10	***Vertical FSO networks with automatic repeat request*** - Using FSO links with a wide coverage optical footprint for multiple users.
11	***Intelligent reflecting surface aided FSO links*** - In the absence of a direct FSO link, it serves as a reflector to direct the incident optical beam to the Rx.

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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

INTRODUCTION

Quantum key distribution 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 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.

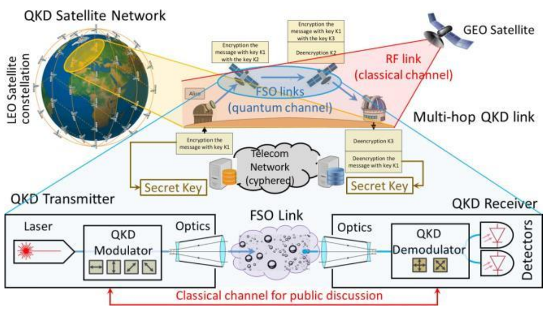

Fig. 1. Overview of a quantum communication system relying on ground-to-space and inter-satellite FSO links to generate quantum- secure keys. Classical (red) and quantum (blue) channels are used to implement the QKD protocol for secure key generation among legitimate/trusted users on ground.

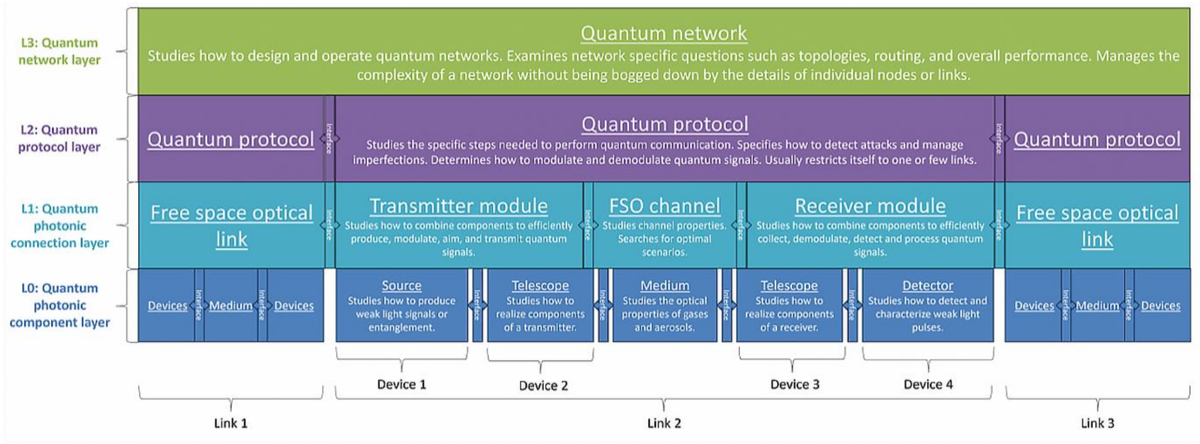

Fig 2. Layered approach used to discuss the different disciplines that are involved in the development of a quantum communication (QKD) network.

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 Tx and Rx). The quantum channel is used for transmitting the quantum states (e.g., single-photon polarization) 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).

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 Tx and Rx 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 number 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 Bennet, G Brassard	1984	DV	HUP
E91	A Ekert	1991	DV	QE
B92	C H Bennet	1992	DV	HUP
Silberhorn	C Silberhorn	2001	CV	QE
DPS	K Inoue, E Warks 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 Tx and Rx 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 Tx and Rx 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 super operator that acts on the density matrices defined by the Tx, inducing a combination of unitary transformations that can be corrected using a single unitary transformation at the Rx. In [8], [9], different models based on the use of unitary operators and super operators 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 Pois- son 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.

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 network 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 qualification, 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, daytime, or nighttime 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 efficiency opt. aberrations
	Atmosph. model	Raman modes, Mie scattering, opt. turbulence
	SPAD	Semiconductors, after pulsing
	SNSPD	Superconductors, hotspots, latching

- 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 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.

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 a 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 synchronisation 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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REVIEW OF LOW-EARTH ORBIT SATELLITE QUANTUM KEY DISTRIBUTION

Davide Orsucci, Amita Shrestha, and Florian Moll

Introduction

The progress in quantum computation hardware is threatening information technology and communication infrastructure as we know it, since quantum algorithms could break the security of currently used public-key cryptographic standards. This threat should be addressed urgently since an adversary could collect massive amounts of encrypted data with the aim of decrypting it once that becomes possible, which is the so-called store-now decrypt-later attack. Two classes of solutions are prominently under consideration to overcome this threat: the use of post-quantum cryptography and **QKD**. Here, we address the QKD approach to solving this problem, since it has the advantage of guaranteeing information-theoretic security and providing long-term secrecy of the exchanged messages.

The implementation of QKD protocols requires optical and photonic building blocks, including dedicated Txs and Rxs that are capable of generating and measuring the quantum states. These elements are currently rather costly, even though their technology readiness level has steadily increased over the past years and several commercial-off the shelf solutions are available today. The most prominent obstacle to the widespread deployment of QKD is the fact that quantum communication can be performed over optical fibres for a distance that are at most a few hundred kilometres, even under the most ideal experimental conditions. This is a consequence of the fact that quantum signals cannot be amplified; therefore, their intensity decays exponentially along an optical fibre and is quickly overcome by noise.

Satellite-based QKD (Sat-QKD) is poised to play a fundamental role in pushing forward the widespread use of this quantum communication technology, as it is currently the only practically viable method for connecting QKD users who are very far apart. Long-distance links can be established using **FSO** communications between satellites and optical terminals on Earth. Furthermore, many system building blocks can be inherited from classical space laser communication systems where technology readiness level is already considerably high. Presently, most of the satellite QKD designs focus on prepare-and-measure (PM) protocols with satellites in low-Earth orbit (LEO), therefore we here focus on this scenario. Other choices of protocols are possible, such as entanglement based or measurement-device-independent methods, but these are significantly more challenging in terms of needed technology. The oldest and most widely investigated PM QKD protocol is the so-called BB84 protocol and it is likely to be the favoured candidate to be employed in future Sat-QKD missions and network constellations [1].

STATE OF THE ART

Trusted node LEO satellite QKD

Near-term Sat-QKD constellations are expected to be used in a trusted-node configuration. In this setting, each satellite is employed to create secure, quantum-generated keys with the authorised user on the ground when a direct LoS with the specified user is available. Suppose that two specific users, customarily called Alice and Bob, already have established a secure key with a satellite and that, at a later moment, they wish to establish a common secure key between them. This can be done by letting the satellite broadcast (e.g., via radio-frequency communication) a value corresponding to the XOR of Alice's and Bob's key, as is illustrated in Fig. 1**Error! Reference source not found.**. This can be interpreted as using Alice's key to encrypt via one-time-pad Bob's key and securely forwarding it to Alice. Alice can then recover Bob's key by XOR-ing the message with her own private key. Note that this architecture relies on the trustworthiness of the satellite node to maintain the overall security of the key exchange.

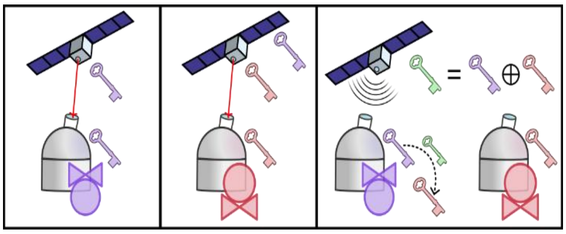

Fig. 2. Concept of satellite-based quantum key distribution to two ground nodes.

Review of recent satellite QKD activities - In the last few years, the interest in Sat-QKD has increased considerably, with many research institutions around the globe pushing to realise and launch LEO satellites that can enable QKD downlinks. Some notable activities include the following ones.

The feasibility of space links was investigated early on at the Matera Laser Ranging Observatory, by demonstrated single-photon level sensitivity by exploiting corner retro-reflectors mounted on a satellite [2]. First experiments of QC from a mobile platform were conducted with a quantum Tx installed in an aircraft and the Rx installed in DLR's Optical Ground Station Oberpfaffenhofen [3]. Another early satellite QC experiment was performed using the SOCRATES (Space Optical Communications Research Advanced Technology Satellite) satellite from NICT (Japan), whereby a QKD-like Tx system was tested for space-to-ground communication [4]. The first full-fledged Sat-QKD demonstration was performed by the Chinese Academy of Sciences employing the Micius satellite. It successfully demonstrated QKD downlink with different ground stations, allowing the exchange of cryptographic keys between Asia and Europe. Furthermore, it demonstrated entanglement based QKD over a distance of 1200 km [5]. ESA has also commissioned studies to assess the potential of Sat-QKD, leading to the kick-off of the SAGA project and of the EAGLE-1 satellite demonstrator. Furthermore, several national aerospace agencies are undertaking the construction of Sat-QKD demonstrators, including for instance QUBE (Germany), QEYSSat (Canada), QT Hub mission (UK), SpeQtral (Singapore), and several more [1].

CHALLENGES AND FUTURE WORKS

The realisation of Sat-QKD terminals must comply with the stringent size, weight, and power (SWaP) requirements of satellite platforms. A promising path to reducing SWaP is the use of photonic integrated chips, which can integrate a complex set of passive and active optical elements (including lasers, phase and amplitude modulators, filters, and more). A fundamental element is the laser terminal that contains the antenna and the beam steering systems. Especially important for the Sat-QKD system is a high gain on the space side to close the link budget and at the same time keep the ground station receive aperture size within tolerable dimensions.
Existing OGS will need to be modified to host QKD Rx modules. Contained detectors need to have high sensitivity at the wavelength of choice. The detectors may be SPADs or superconducting-nanowire single-photon detectors; the latter showcase very high detection efficiencies (often exceeding 90 %) but are still complex and bulky systems requiring cryogenic cooling. In the case of single-mode fiber interfaces maturity and efficiency of adaptive optics systems need to be increased. The main contribution to the transmission loss stems from the beam divergence since (even for diffraction-limited beams) a satellite-to-ground link results in a spot on the ground that is much larger than the aperture of existing OGS; other factors include atmospheric scattering and absorption, free-space-coupling or fibre-coupling of the incoming photons, pointing inaccuracy, and internal Rx and detector inefficiencies. Thus, link losses will realistically be at least -40dB. Eventually this also triggers the need of high rate QKD Txs to generate sufficient key material.

The operating wavelength Sat-QKD should be selected to optimise the performance and minimise the system complexity. Typical choices exploit the atmospheric transparency windows either in the near-IR band (around 850nm) or in the C-band (around 1550 nm). The NIR band suffers from increased background light and slightly higher atmospheric absorption, but it has less diffraction losses; furthermore, silicon detectors operating in the NIR band tend to have lower noise levels than the InGaAs detectors required for operations in the C-band. The C-band main advantage is the fact that it can benefit from the availability of many commercial off-the-shelf solutions developed for optical fibre classical communication.

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ATMOSPHERIC STATE INFORMATION FOR LONG-RANGE FSO COMMUNICATION

Niek Doelman, Eszter Udvary, Yalçın Ata, Stefanie Häusler, Thai-Chien Bui, and Loes Scheers

INTRODUCTION

Long-range **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.

In regular FSO communication systems, 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) QKD. Whereas in regular optical fiber communication systems the signal can be amplified (in optical or electrical domains) in order to achieve a sufficient SNR. Note that 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.

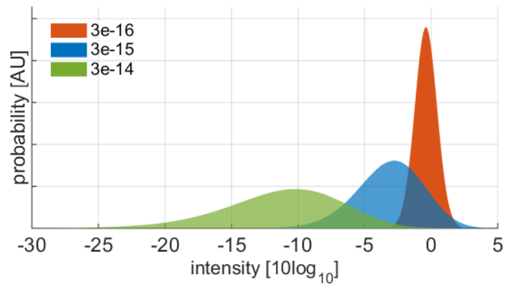

Fig. 1. Probability distributions of received, turbulence-induced intensity fluctuations in an exemplary 5 km horizontal FSO link for various C_n^2 values.

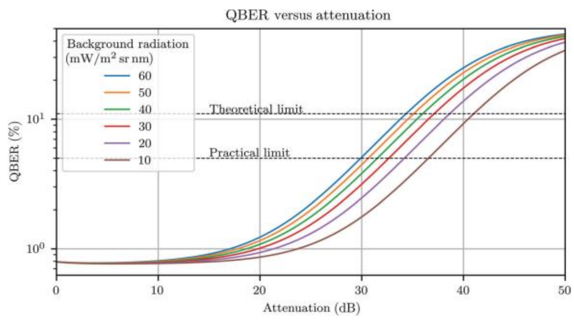

Fig. 2. Dependency of QBER and attenuation for different background radiation levels in an exemplary QKD scenario [1].

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:

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

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 $\tilde{C}_n^2$ 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, 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.

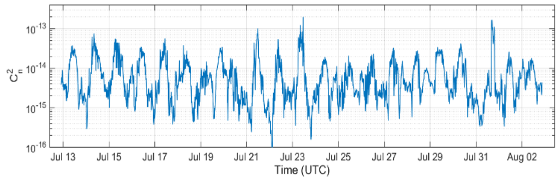

Fig. 3. Measured C_n^2 values at ground level during a 3 weeks field test with an optical feeder link, Cabouw NL in 2022 [4].

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 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 Tx 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].

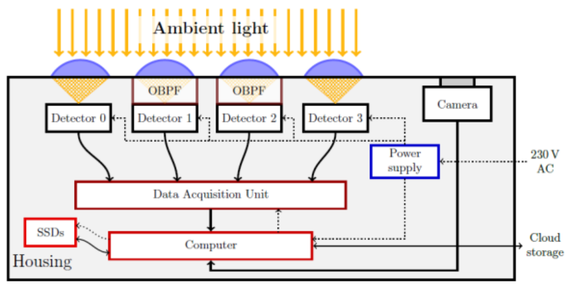

Fig. 4. Block diagram of the background light measurement station.

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-IR 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.

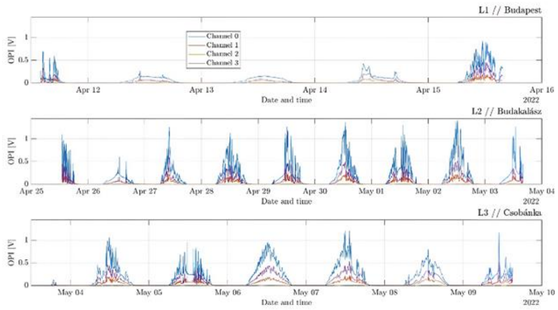

Fig. 5. Measured background sky radiation over several days and 3 locations in Hungary [5].

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 Rx. 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 1540 nm IR channel is low compared to that in the 810 nm channel; this meets the expectations based on the sun's emission.

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 I.

Table I. 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 OGS and/or space terminals - when the atmospheric conditions would necessitate that.

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WAVELENGTH DIVISION MULTIPLEXING FREE SPACE OPTICAL LINKS

Giulio Cossu, Veronica Spirito, Michail P. Ninos, and Ernesto Ciaramella

INTRODUCTION

Nowadays **free space optical communications (FSOC)** are entering into the domain of satellite communications thanks to their shorter wavelength, providing much higher capacity than the traditional RF wireless communications. High-speed satellite links are becoming of paramount importance for different purposes such as Earth observation, disaster recovery, last mile access of white areas, and they should exploit FSOCs to establish different types of links, such as feeder links (FLs), inter-satellite links (ISLs) or deep space links. This scenario is presented schematically in Fig. 1.

The use of optical beams shows other several benefits, such as the large modulation bandwidth, the high directivity, the reduction of the required SWaP compared to RF-based systems. Last, but not least, optical beams can prevent interference between near carriers by using the unlicensed spectrum of the optical frequencies.

Leveraging upon the huge technological developments in fiber communications, the step forward can be accomplished with non-negligible, yet limited, technological effort with practical results of cost/benefit analysis. Very high-throughput traffic can be achieved by means of the well-known WDM technique. This is schematically represented in Fig. 2, where all WDM channels are combined and amplified by a booster erbium-doped fiber amplifier (EDFA) and launched into free-space by the telescope. After free-space propagation, the beam is collected by the Rx telescope, coupled into a single-mode fiber and amplified by a low-noise EDFA pre-amplifier. Finally, the channels are demultiplexed and the signals are detected by the corresponding optical Rx architecture. Using this type of links, FSOC with Terabit/s capacities were demonstrated terrestrial links [1]; they can now be taken to the satellite communications.

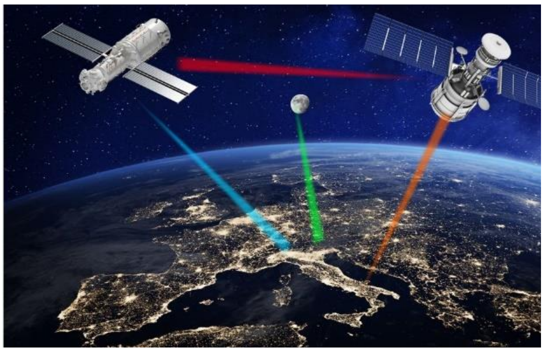

Fig. 1. Pictorial view of the different FSOC links: two FLs, one ISL and one deep-space link.

To reach this target, however, relevant innovations still must be introduced, such as new telescopes, interfacing free-space and fiber-based transceivers, and, of course, space-qualification of existing photonic components. However, the most challenging issues are related to the channel in FLs, where light is passing through the atmospheric layers, either in uplink or downlink. The atmosphere can attenuate the intensity and distort the wavefront of the optical signals, on millisecond timescales, leading to unpredictable fading events. To counteract these impairments, adaptive optics systems along with optimized acquisition and tracking methods should be deployed at the OGS site. Here, we provide an overview of the emerging topic of WDM-FSOC in satellite networks and the key elements that must be considered when designing the links. We also highlight the technical gaps that should be addressed.

STATE OF THE ART

Space agencies and private companies are heavily investing for developing prototypes to establish ISLs and the most challenging FLs. NASA project TeraByte InfraRed Delivery (TBIRD) aims in demonstrating a direct LEO-to-ground downlink (FL) laser communication link form a CubeSat towards a special ground terminal by NASA, providing a maximum data rate of 200 Gbit/s [2]. This high data rate is achieved by leveraging on off-the-shelf fiber-based coherent transceivers directly exploited in space applications. Recently, NASA announced that TBIRD completed the first batch of measurements, transmitting to ground 1.4 TB of data in a single pass of about five minutes (~ 40 Gb/s, on average).

The Lunar Laser Communications Demonstration (LLCD) was undertaken by NASA to demonstrate FSO between Moon and Earth. LLCD consisted of a duplex laser communication between a satellite in lunar orbit and a ground terminal on Earth, the Lunar Lasercom Ground Terminal (LLGT), a transportable system that was located in New Mexico. The communication was based on the optical C-band, the tests demonstrated the feasibility of a downlink transmission at 622 Mb/s and 20 Mb/s for the uplink. Sophisticated technologies were developed and used in these tests, such as superconductive nanowire detectors. The same ground station will support the Laser Communication Relay Demonstration (LCRD) [3], a long-term mission to demonstrate a bidirectional 1.2 Gb/s optical link between the ground and geosynchronous equatorial orbit (GEO) satellite.

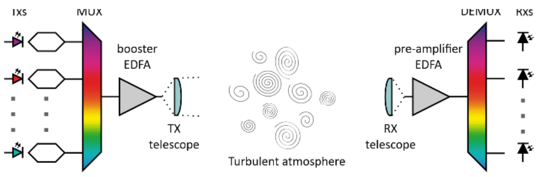

Fig. 2. Scheme of a typical transparent WDM-FSO system.

The ESA "High thRoughput Optical Network" (HydRON) initiative aims to develop a "fiber in the sky" network providing seamless connectivity among different types of satellites, in various orbits, with the terrestrial networks: HydRON should integrate both space and ground segments into a high-capacity network [4]. This involves considering various payload configurations and network structures, while also considering different orbital characteristics, such as LEO and GEO. Mission requirements, payload specifications, platform limitations, ground segment requirements, and network/protocol requirements should be taken into account, and preliminary designs are developed for the different scenarios under investigation.

Japan Aerospace eXploration Agency's (JAXA) Japanese Data Relay System (JDRS) program for Earth observation is already using an FSOC inter-orbit link between a spacecraft in low orbit and the data relay satellites. The new satellite carries a laser utilizing communication system by JAXA. It uses the IR light to facilitate inter-satellite links at a data rate up to 1.8 Gb/s. The satellite will operate in a geostationary orbit around 36000 km altitude, relaying data between Japanese satellites. Data is downlinked via an RF Ka-band connection to the ground station.

In France, ONERA Labs are currently developing and integrating a novel OGS for FLs, addressing both GEO and LEO orbits, within the framework of the project FEELINGS. This OGS will be based on a 60 cm diameter telescope, embedding a high-power laser source, targeting 25 Gb/s DPSK links. The system should be launched by mid-2023 **Error! Reference source not found.**. Another project by ONERA was the FEEDELIO experiment. Here, the aim was to demonstrate the effectiveness of the adaptive optics pre-compensation of atmospheric turbulence in presence of induced anisoplanatism. The demonstration has been performed from the Tenerife OGS and a terminal breadboard emulating a GEO satellite at a distance of 13 km, on top of mount Teide.

In Germany, other relevant experiments were conducted by the German Aerospace Center (DLR). As an example, the Optical Space Infrared Downlink System (OSIRIS) aims at developing downlinks from small satellites (and direct link between them). Depending on the configuration, the data rates range from 100 Mbit/s (for small satellite platform) to ~10 Gbit/s (for larger spacecrafts).

The Australian Space Agency recently demonstrated in a field trial a potential solution to mitigate atmospheric effects, maintaining stable pointing to a moving target. They demonstrated a robust, high-speed coherent FSOC between an optical terminal and a drone moving with angular velocity comparable with the one of a LEO satellite. By integrating Machine Vision optical tracking and tip/tilt adaptive optics technology, both beam pointing and the angle-of-arrival were stabilized despite the presence of atmospheric turbulence. This allowed to maintain a horizontal link stable at 100 Gb/s.

CHALLENGES AND FUTURE WORKS

In FSOC links, the limited divergence of the optical beam allows for higher irradiance at the RX but, at the same time, it increases the need for precise alignments, which must remain stable during the communication. This task is carried out by the pointing, acquisition, and tracking subsystem. Nonetheless, the communication performance can be affected even under perfect alignment, due to the residual pointing jitter, which arises due to random angular fluctuations induced by the atmospheric turbulence and the unavoidable vibrations in mechanical structures.

In addition, in FLs, the optical signal passes through the atmosphere, suffering from several effects, shortly summarized in the following. Absorption and scattering produce a wavelength-dependent intensity attenuation that increases with decreasing the elevation angle and the OGS altitude. They are well-known deterministic effects, and their impact can be straightforwardly estimated. The atmospheric turbulence is caused by wind and temperature gradients, which create eddies of air with varying densities and, thus, different refractive indices. These eddies can act like prisms and lenses, eventually producing a signal with an intensity that changes over time and space, an effect indicated as scintillation. To describe these intensity fluctuations, different statistical models have been proposed, but there is yet a lack of experimental evidence to strongly support any of them. Another important point to consider is the temporal nature of turbulence. In most practical cases, the channel fading changes very slowly, and the channel coherence time is usually between 0.1 and 10 ms.

Light passing through eddies on the order of (or larger than) the beam diameter (e.g., in feeder uplink), experience a phase modulation that combined with free-space propagation, results in a beam randomly moving around its boresight on the Rx plane, i.e., beam wander. Therefore, a beam emitted by an OGS towards a satellite can experience a significant angular displacement, on the order of several µrad. In downlink, the situation is different as the beam enters the atmosphere with a diameter much larger than the eddies of the atmosphere, because of the free-space beam expansion, and thus is affected minimally by beam wander effects.

In addition, in order to exploit the WDM technology in FSOC systems, the Rx telescopes must be able to couple the light into a single mode fiber. Under optimal conditions, the diameter of the focused beam should be the same as that of the single mode fiber guided mode, thus resulting in a coupling loss of 2-4 dB.

To (partially) counteract these effects, it is possible to act at communication or at hardware level. Alternative modulation/detection schemes can be exploited to increase the robustness, possibly combined with other common techniques (e.g., forward error correction). Moreover, the OGS should be equipped with adaptive optics, commonly used in optical astronomy. By employing this technique, the distortion induced in the signal wavefront by the turbulence is reduced by means of wavefront sensors and deformable mirrors. adaptive optics could allow to recover the signal wavefront in downlink and minimize the scintillation in uplink. In the last case, however, adaptive optics requires that the downlink and uplink signals have the same atmospheric path. Otherwise, anisoplanatic effects can limit the efficiency of adaptive optics subsystem. Unfortunately, importing adaptive optics imaging technology into the communications field is not straightforward since it requires much stricter requirements.

Finally, the background noise can also degrade the performance of the FSOC links. The Rx lens, especially in the terrestrial environment, collects also some undesirable and non-negligible background radiation, which can fall within the frequency range of the detectors as well as the optical bandpass filters, deteriorating the optical signal-to-noise ratio.

In conclusion, we presented an overview of WDM-FSOC links. The key open challenges are related to the actual implementation of such systems in real environments, since there is still lack of a reliable channel model, i.e., validated over different conditions. Crucial technological developments also include wide-size telescopes, with accurate PAT, powerful adaptive optics, and very good robustness against pointing errors. Another strategic element is the development of very high-power optical amplifiers, which can compensate for the losses, typically very high.

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Free Space Optical Communication in the Mid-IR for Future Long-range Terrestrial and Space Applications

Xiaodan Pang and Carlo Sirtori

Introduction

As the data rate demand for next-generation wireless communication technologies (6G) increases, an all-spectrum communication paradigm has been proposed to facilitate cooperative free-space communications using both optics and radio, offering ultra-broad spectral resources [1]. **FSO** has recently emerged as a potential candidate to complement radio technologies for both terrestrial and space communications, including fixed mobile x-haul links (front-, mid-, and backhaul), ground-to-satellite communications, and inter-satellite communications. Conventional FSO communications in the near-IR telecom band, though technologically mature for deployment by reusing fiber-optic telecom components and devices, face several challenges that impact their performance and practicality. These include atmospheric attenuation, weather sensitivity, such as susceptibility to particle scattering and turbulence effects, which can degrade signal quality, and eye safety concerns due to the potential harm caused by NIR wavelengths. To date, these issues have hindered the wide deployment and scalability of FSO communications to be a reliable part of the ICT infrastructure. Consequently, the research community explores and proposes other spectral regions for FSO applications.

Among various spectral regions, the mid-wave infrared (MWIR, 3-5 µm, 60-100 THz) and long-wave infrared (LWIR, 8-12 µm, 25-37 THz) in the mid-infrared (MIR) region hold significant potential for FSO technologies. They offer lower atmospheric propagation attenuation, broader unlicensed bandwidth, higher resilience against adverse weather conditions, and lower eye safety risks compared to other frequency bands [2]. However, the MWIR and LWIR spectral regions for FSO applications have been underexploited due to the lack of efficient and effective transceiver technologies, as the semiconductor lasers and detectors operating at the NIR telecom band cannot be straightforwardly reused. Currently, the research community observes encouraging efforts and results in the research and development of MWIR and LWIR FSO communications from both the device and the system level. High data rate transmissions are made possible in these spectral regions with various approaches, progressing at an even faster pace than fiber-optic communications in recent years.

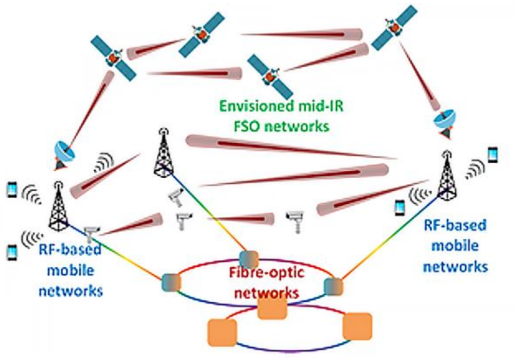

Fig. 1. Envisioned mid-IR FSO networks as a part of next-generation ICT infrastructure operating in parallel with the fibre-optic and the RF-based mobile networks.

STATE OF THE ART

There are two primary photonic approaches to generating and detecting signals for free-space communications in the MWIR/LWIR range: wavelength conversion and directly emitting laser sources. The wavelength conversion-based mid-IR FSO systems utilize well-developed telecom transceivers and difference frequency generation (DFG) to convert signal wavelengths between 1.5 µm and mid-IR. While these systems have reported high data rates, they suffer from high-power consumption, energy deficiency, and hardware complexity, hindering their practical development. The wavelength conversion approach reuses mature optical and optoelectronic components from fiber-optic systems for free-space transmissions. Wavelength conversion from the telecom band is achieved using nonlinear parametric conversions in periodically poled LiNbO3 (PPLN) devices. This allows the Tx and Rx to operate directly in the telecom band, e.g., 1.55 µm. With this approach, data rates of MWIR free-space links can keep up with fiber-optic systems, achieving up to 300 Gb/s aggregated data rates [3]. Advantages include very high data rates, compatibility with fiber-optic systems, and quick installation for high-end applications. However, drawbacks include limitations to the sub-4 µm region, high pump power requirements, low energy efficiency, and bulky PPLN devices.

The second approach, which involves direct emission laser sources and modulators in the MWIR and LWIR regions, provides numerous benefits such as superior energy efficiency, easy integration, and the absence of power loss due to frequency conversion. One early example of this technology utilized a PbCdS diode laser operating at a wavelength of 3.5 µm to transmit data at a rate of 100 Mb/s. Direct-emission semiconductor components and devices, including quantum cascade lasers (QCLs), interband cascade lasers (ICLs), external Stark-effect modulators, quantum cascade detectors, and quantum well IR photodetectors, among others, present more promising long-term solutions by enabling compact semiconductor transceivers for free-space communications. QCLs operate using inter-subband transitions, which cover a broad wavelength range extending from the MIR to THz regions. These lasers exhibit significant advancements in terms of wide bandwidth, high-temperature operation, and low energy consumption.

Directly modulated (DM) QCLs are particularly noteworthy due to their ultra-short carrier relaxation lifetimes, which result in high intrinsic modulation bandwidth and an over-damped laser response. This suppression of resonance frequency makes DM QCLs suitable for a wide array of applications, including free-space communications. Since the early 2000s, several demonstrations based on DM QCLs have reported data rates reaching up to a few Gb/s. After the invention of THz QCLs in 2007, transmission experiments achieved data rates of up to tens of Mb/s also in the THz region. While these initial demonstrations required cryogenic temperatures, subsequent developments enabled room-temperature broadband modulation of QCLs in the MWIR and LWIR regions. Consequently, numerous QCL-based

Table I. Summary of lab demonstrations of quantum/interband cascade devices-enabled free-space transmissions.

Wavelength (μm)	Data rate / bandwidth [a]	Year
7.3	10 MHz [b]	2001
9.3	330 MHz / 115 kb/s	2001
8.1	2.5 Gb/s	2002
8.1	750 MHZ-1.5 GHz	2002
73	580 kHz	2007
10.46	20 kHz	2008
3	70 Mb/s	2010
72.6	1 Mb/s	2013
77	5 Mb/s	2013
92	20 Mb/s	2015
4.7	40 MHz	2015
Mid-IR [c]	20 MHz	2015
10.6	1 Gb/s	2019
4.65	3 Gb/s	2017
4.65	4 Gb/s	2017
4.65	6 Gb/s	2021
4	680 Mb/s	2022
9.6	11 Gb/s	2022
8.6	12 Gb/s	2022
4.1	16 Gb/s	2022
9.15	8.1 Gb/s	2022
9	30 Gb/s	2022

[a] The data rate for digital transmission, and modulation bandwidth for analog transmission are listed, respectively; [b] modulated on to a 66 MHz carrier; [c] wavelength not explicitly specified.

free-space transmission demonstrations at room temperature have been reported.

Furthermore, recent efforts involving alternative schemes, such as DM ICLs and external Stark-effect modulators, have yielded encouraging and promising results. These advances in direct emission laser sources and modulators for the MWIR and LWIR regions continue to pave the way for more efficient, high-performance, and versatile free-space communication systems.

Table I summarizes representative lab demonstrations with solid-state direct-emission MIR transceivers, including DM QCLs [4], directly modulated ICLs, and external Stark-effect modulators [5]. It is evident that there is a growing momentum in the field of direct emission transceivers for free-space communication systems, with rapid advancements being made in recent years. Based on the current trend, it is reasonable to anticipate that data rates exceeding 100 Gb/s will be achieved with direct emission transceivers in the near future. This progress will help bridge the gap between MIR FSO systems and fiber-optic systems. These recent developments present a promising trajectory for the evolution of FSO technology, addressing the ever-increasing demand for high data rates in next-generation wireless communication technologies such as 6G. By offering a more energy-efficient and practical solution, direct emission transceivers in the MWIR and LWIR regions will play a crucial role in shaping the future landscape of wireless communication systems. As the technology continues to mature, further research and development will be necessary to optimize the performance of direct emission transceivers, ensuring their ability to meet the complex and diverse requirements of various applications. Nonetheless, the ongoing progress in this area instills confidence that these emerging technologies will be instrumental in shaping the future of high-speed, energy-efficient, and robust free-space optical communication networks.

HALLENGES AND FUTURE WORKS

A. *High-efficient transceiver technologies for system integration and miniaturization*

The development of efficient, high-performance, and reliable transmission, modulation, and detection devices in the MWIR and LWIR bands to match the maturity level of fiber-optic NIR transceivers remains a significant challenge. Specifically, there is a need for effective phase modulation and coherent detection in these bands to enable the use of complex modulation formats in digital coherent optical transmissions. This necessitates the invention of novel devices with advanced capabilities.

One such capability is wavelength tunability, which allows the transceiver to operate over a range of wavelengths, enhancing the flexibility and adaptability of the system. This is crucial for optimizing spectrum utilization with WDM, accommodating various transmission distances, and potentially supporting dynamic FSO network reconfiguration. Developing tunable devices in the MWIR and LWIR bands requires innovative approaches, such as leveraging new materials or implementing unique device designs, to overcome the inherent limitations of existing technologies.

Additionally, high-temperature operation capability is essential for the deployment of MWIR and LWIR systems in demanding environments, such as industrial settings, aerospace, or defense applications. Devices with high-temperature operation capabilities can withstand harsh conditions and maintain optimal performance, thereby improving the overall reliability and robustness of the communication system. Achieving this capability necessitates research into temperature-resistant materials, improved thermal management techniques, and the development of device architectures that minimize the impact of temperature variations on performance.

Therefore, to advance MWIR and LWIR technology towards the maturity level of fiber-optic NIR transceivers, a multidisciplinary approach will be required, combining expertise in material science, device engineering, and optical communication systems, to ensure that the developed technologies meet the stringent requirements of next-generation FSO communication networks.

B. Reinvent and develop active/passive optical components for MWIR and LWIR

In addition to the transceivers, the technology readiness level (TRL) for other essential devices operating in the MWIR and LWIR bands is relatively lower compared to those in other spectral windows. Developing mature components and systems for these bands demands substantial research and investment in various aspects of optical communication technology.

Many active and passive optical components that are crucial for setting up viable FSO networks, such as amplifiers, filters, (de-)multiplexers for both wavelengths and polarizations, and wavelength-selective switches (WSS), need to be reinvented for MWIR and LWIR operation. This entails overcoming a range of technical challenges, such as designing new materials and device structures that are compatible with these spectral bands, ensuring adequate performance, and maintaining cost-effectiveness. Amplifiers, for instance, must be redesigned to provide sufficient gain and low noise levels in the MWIR and LWIR bands. This may involve investigating novel gain materials or developing new pumping schemes to optimize amplifier performance in these bands. Filters and (de-)multiplexers must be adapted to function effectively in the MWIR and LWIR bands, providing precise wavelength selectivity and low insertion loss. This may require exploring new filtering mechanisms or leveraging advanced fabrication techniques to create compact, high-performance devices.

WSS, which are vital for flexible and dynamic FSO network routing, must also be developed for the MWIR and LWIR bands. Achieving this goal may involve researching new switching technologies or optimizing existing designs to ensure efficient, fast, and reliable operation in these spectral regions. Moreover, efforts to increase the TRL of MWIR and LWIR devices should encompass improving their durability, power efficiency, and ease of integration into existing and future optical communication systems. This will necessitate close collaboration between researchers, engineers, and industry stakeholders to ensure a smooth transition from laboratory prototypes to commercially viable products.

C. Optimal modulation, coding and multiplexing schemes for MWIR and LWIR

The MWIR and LWIR bands are situated between the RF and NIR fiber-optic wavelengths, which results in an optimal trade-off between bandwidth and SNR. This balance affects various aspects of communication, such as serial versus parallel transmission, single-carrier versus multi-carrier systems, and binary versus multilevel formats.

In addition to the optimal modulation and coding schemes as determined by information theory, other practical considerations must be taken into account when configuring modulation, coding, and multiplexing for MWIR and LWIR FSO systems. Factors such as resilience against adverse weather conditions, for example, will play a crucial role in the design and implementation of these systems. Particularly, atmospheric turbulence can still impact signal quality and overall performance of MWIR and LWIR FSO systems. To mitigate these effects, cooperative transmission of FSO with RF in the mmWave or THz band can be considered. This approach allows for the combination of the benefits of both FSO and RF technologies, providing more robust communication links that can adapt to different atmospheric conditions and maintain high data rates. Moreover, adaptive techniques can be employed to optimize the communication system's performance under varying conditions. These may include dynamic adjustments to the modulation and coding schemes or the implementation of advanced error correction techniques to improve the system's resilience against atmospheric turbulence and other environmental challenges.

D. Free-space routing for NLOS scenarios

Lastly, a wide range of applications calls for support in non-LoS use cases. N0n-LoS situations can lead to various challenges, such as signal obstruction, absorption, scattering, and multipath effects, which can significantly impact the performance and reliability of communication systems. To address these challenges, researchers are exploring several potential avenues, including:

- *Beam steering and tracking*: Implementing advanced techniques to precisely control the direction and angle of the transmitted beams, enabling them to bypass obstacles and maintain strong communication links despite NLoS conditions.
- *Adaptive optics for MWIR and LWIR wavelengths*: Developing new optical technologies that can adapt to changing environmental conditions and mitigate the effects of atmospheric turbulence, scattering, and absorption, ensuring robust and reliable communication links in non-LoS scenarios.
- *Multi-hop and/or relay-assisted communications*: Utilizing multiple intermediate nodes or relay stations to relay signals between the Tx and Rx, circumventing obstructions and maintaining connectivity in N-non-LoS situations.
- *Distributed multiple-input multiple-output (D-MIMO) systems with joint transmission functions*: Implementing MIMO technology, which employs multiple Txs and Rxs located separately to send and receive multiple data streams simultaneously, in combination with joint transmission functions to coordinate and optimize data transmission in non-LoS environments.

While these potential solutions offer promising avenues to tackle the challenges associated with NLoS use cases in MWIR and LWIR FSO systems, further research and development are necessary to refine these strategies, enhance their effectiveness, and ultimately improve the overall performance and reliability of non-LoS FSO communications. Such research will help ensure that MWIR and LWIR FSO systems can effectively support a wide range of applications in diverse and challenging environments.

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REVIEW OF HYBRID OPTICAL-RADIO INTER-SATELLITE LINKS IN 6G NTN INCLUDING QUANTUM SECURITY

Joan Bas and Marc Amay

INTRODUCTION

Current mobile communication systems have started to integrate non-terrestrial networks to mobile systems (from Release 17 of 3rd generation partnership project (3GPP)). So, new applications such as direct-to-phone from a satellite are being intensively investigated in the framework of 3GPP and 5G. In this scenario, mega-satellite constellations are being deployed /will be deployed to provide IoT and broadband services according to the requirements of 5G/beyond5G/6G (sixth generation). These satellite constellations will provide global coverage, capacity and security as well as will complement the terrestrial infrastructure. These new satellite constellations will interconnect the satellites among them. The so-called inter-satellite-links (ISL). These links, according to 3GPP can be radio (millimetre waves) and optical, see **Error! Reference source not found.**.

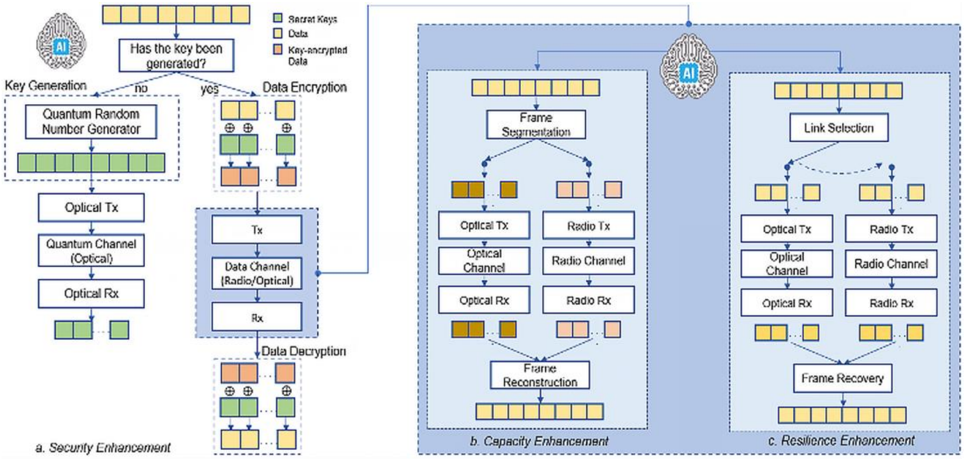

Fig. 1. Capacity, Resilient and Security schemes for hybrid optical-radio systems.

Toward this regard, both SpaceX (Starlink), Amazon (Project Kuiper) and OneWeb, and Telsesat will use in their future mega-constellations of satellites optical inter-satellite links. On the contrary, Boeing plans to inter-connect the satellite of its constellation using mmWave links (i.e., the V-band). Notice also that the satellite constellations equipped with inter-satellite links introduces a level of flexibility in the communications that permit to increase; the resilience to potential malfunction of the satellites; re-route the traffic to under-used satellites; extend the coverage with a lower number of satellites; avoid eavesdropping from tactical satellites; to develop multi-service constellations. Note that inter-satellite links may have different capacities. Thus, low, and high data rate services may be implemented in the same infrastructure (e.g., IoT, broadband connectivity, and others) and multiple operators can simultaneously operate in the same infrastructure. By doing so, the operating expenses, cost of maintenance, (operational expenditure (OPEX) and capital expenditure (CAPEX)) and the service cost are reduced.

STATE-OF-THE-ART

The development of optical links to connect two satellites is quite recent. The first connection between two satellites using the optical bands was made in November 2001 between ESA's Artemis satellite located in GEO orbit and Centre National D'Etudes Spatiales Earth observation satellite called SPOT 4, which is in LEO orbit **Error! Reference source not found.** (a transmission distance of 40,000 km and a data rate of 50 Mbps). In 2005, ARTEMIS satellite began to be tested for bidirectional relay with the KIRAKI satellite of the JAXA **Error! Reference source not found.**. In 2014, ESA made the first link between satellites at gigabit speeds when the Alphasat TDP1 GEO satellites and the Sentinel-1A LEO satellites were connected **Error! Reference source not found.**. Since then, multiple optical links have been made between the two satellites of a quasi-operational and experimental nature. The success of this system suggests that it may be applied to other links such as GEO-GEO (a transmission distance reaching up to 75000 km).

Similarly, the Sentinel 2A satellite was launched in October 2015 and was also equipped with inter-satellite optical links that were employed to connect with the Alphasat satellite. Investigations with the Sentinel 1A and 2A satellites gave way to what is known as the European data relay system (EDRS), which consists of a network of two GEO satellites that provide relay services to LEO satellites. The EDRS system has both optical inter-satellite and radio connection in the Ka band. The first ERDS satellite, called EDRS-A, is operated by Eutelsat (France) and has been active since December 2016 and is known as EUTELSAT 9B EAST **Error! Reference source not found.**. In November 2020 the JAXA carried out its own EDRS, which is called laser utilizing communication system (LUCAS), which made a link between a GEO and LEO satellites.

CHALLENGES AND FUTURE WORK

Inter-satellite links allow communication between two satellites using either radio or optical frequency bands. However, its extension to satellite constellations presents several challenges including: (i) develop of low-cost coherent detectors; (ii) reduce the acquisition time of the links, especially for inter-orbit satellite links; (iii) to develop high-capacity systems but also resilient to impairments, see Fig. 1; and (iv) integrate the quantum links with the ISL links.

Toward this regard the future work may help to cope with the aforementioned challenges: (*i*) take advantage of the low temperatures of the space to integrate superconductivity elements to increase the capacity of radio and optical systems; (*ii*) introduce nanotechnology to miniaturize the radio and optical payload; (*iii*) introduce artificial intelligence to combine capacity and resilience communication schemes; (*iv*) develop quantum communication schemes for satellite with a large secrecy key rate by: decoupling the data and quantum channel using MEC techniques; resorting to signal processing combined with advanced coding schemes; use spatial diversity; utilize artificial intelligence to manage the quantum keys; and (*v*) extending the payload regeneration to include the quantum key distribution along a quantum satellite network.

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PERSPECTIVES FOR GLOBAL-SCALE QUANTUM KEY DISTRIBUTION VIA UPLINK TO GEOSTATIONARY SATELLITES

Davide Orsucci, Amita Shrestha, and Florian Moll

INTRODUCTION

In this white paper, we analyse an unconventional satellite quantum key distribution (Sat-QKD) design where a single large satellite in GEO allows the distribution of secure keys to many users. This design involves the use of many parallel uplink quantum channels, each supporting a prepare-and-measure **quantum key distribution** protocol, such as BB84. Hundreds of users in the FOV of the GEO satellite may be served simultaneously and using a wide FOV telescope may provide coverage to a whole continent at each time. By adjusting the satellite's pointing the field-of-regard can be further extended and all users located within the Earth's hemisphere visible from the GEO satellite could eventually establish a QKD link with it. Therefore, a single satellite could ultimately provide keys to a vast number of users, potentially hundreds of thousands, a task that would otherwise necessitate a large constellation of tens or hundreds of LEO satellites. The goal of this approach to Sat-QKD is to shift expenses from the users to the satellite QKD provider and obtain cost savings from parallel access from many users. However, given the very large distance between a GEO satellite and the ground (35,790 km - 41,590 km depending on the specific location of a user on Earth), a very large aperture telescope, similar in size to the Hubble space telescope, is required to close the link budget, i.e., to obtain a non-zero secure key rate generation. Such telescope systems are currently extremely expensive, in the billion Euros range. However, the advantage of using such a telescope is that would be able, in principle, to serve many users (hundreds or thousands) simultaneously, while in most QKD concepts with LEO satellites each satellite can be linked to only one user on the ground at a time.

STATE OF THE ART

The approach to Sat-QKD hereby presented is novel and deviates from conventional designs. Thus, there is no existing literature on this topic and this section will therefore focus on a preliminary concepts and ideas, which may lead to future more in-depth investigations.

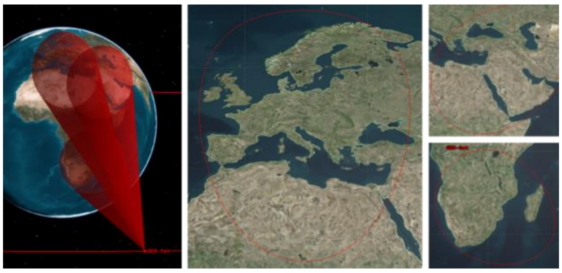

Fig. 3. Illustration of the field of view of the telescope, which can cover a continent at a time. By periodically adjusting the pointing of the telescope, the field of regard can be extended to cover almost half of Earth's surface.

Advantages of employing a geostationary orbit

Using an uplink to a GEO satellite for QKD offers several advantages. User only need to own laser terminals, which are cheaper than single photon detectors. Also, since the GEO satellite maintains a nearly constant position in the sky, only fine-steering mirrors are needed for pointing the terminal; costs are reduced, compared to QKD with LEO satellites, since a non-moving modestly sized laser terminal (25 cm aperture) suffices. Another advantage is that links to GEO satellites have a small point-ahead angle (around 20 µrad), which is typically within the atmospheric isoplanatic angle. This allows for effective compensation of beam wander in the uplink by tracking the apparent position of the downlink beacon sent from the satellite. As a final advantage, GEO satellites may have a long lifetime due to the absence of atmospheric drag. The lifetime limit could be determined by mirror degradation, or by the evaporation of coolant if evaporative cooling is required for maintaining the detectors at cryogenic temperatures.

Satellite design

The concept design requires that the telescope is fit with several single-mode fibre (SMF) couplers located in the focal plane. The optical fibres then lead to a single-photon detecting system hosting hundreds of channels (i.e., detectors) in parallel. Each set of four channels would be used to implement an independent Rx front-end for a polarisation-encoded BB84 link. The satellite would be used in a trusted-node configuration, similarly to the case presented in the chapter "Review of low-Earth orbit satellite quantum key distribution". To streamline the presentation, we only consider 1550nm as QKD wavelength, in which the atmosphere is very transparent and for which mature laser communication technologies already exist.

To achieve positive QKD generation rate, the telescope aperture diameter needs to be very large (around 2 m). The telescope configuration could be, e.g., an off-axis three-mirror anastigmat (TMA); the off-axis TMA design effectively corrects all major aberrations and avoids having a central obscuration. As a result, the point-spread function (PSF) is ideally described by a Bessel function, leading to higher SMF coupling efficiency. In contrast, a central obscuration would cause the PSF to have an irregular shape, resulting in lower coupling efficiency. We consider a 3.1° semi-aperture viewing angle, which corresponds to approximately 8 square degrees of FOV.

The hundreds of individual beams sent in uplink by the users are convoyed towards optical fibre couplers located into the focal plane. An active switch and routing system, based for instance on micro-electromechanical mirror system or liquid variable lenses, needs to be employed to steer each individual beam to a fibre coupler.

After coupling to SMFs, the optical signals are conveyed to the single photon detectors required for the quantum communication. We suggest using SNSPDs. Though complex, these detectors offer high detection efficiency and low dark counts. At present, there are only a few theoretical articles addressing the use of SNSPDs in space [1] and achieving the required cryogenic temperatures in space is challenging. However, provided that a cryostat is available on-board, it should be relatively straightforward to accommodate hundreds of SNSPD channels within it.

Link budget estimation

We present a link budget estimation for the considered scenario, including the most relevant factors that influence the communication quality between the ground station and the satellite. The results are summarised in Table I. The Tx (Tx) antenna gain is calculated by assuming a truncated Gaussian beam with a waist (beam radius at $1/e^2$ of the peak intensity) of 15 cm in a terminal with a 25 cm diameter aperture, using the approach from [2]. The channel loss is determined for the challenging case where the user sees the satellite at an elevation angle is 30° and the link distance is around

38000 km. For nominal atmospheric visibility conditions (23 km) the atmospheric absorption is rather small. For nominal turbulence strength (Hufnager-Valley 5/7 turbulence model) the loss due to beam spread is substantial, even if the beam wander is fully corrected [3]. The Rx antenna gain is determined assuming a telescope having a 2 m clear aperture. Several mirrors will be required for steering the beam, incurring in some optical losses even if highly reflective gold-coated mirrors are employed. Fibre coupling efficiencies exceeding 67% can probably be achieved [4], since the laser light wavefronts in uplink are almost perfectly planar.

Table I. Link Budget estimation for the considered scenario.

Parameter	Value [a]	Reference
Wavelength	1550 nm	assumption
Tx antenna gain	112.3 dB	Ø 25cm, waist 15cm, M2: 1.2 [2]
Free space loss	-289.8 dB	distance 38600km
Atmospheric loss	-0.7 dB	el. 30°, visibility 23km
Beam spread loss	-3.4 dB	el. 30°, HV 5/7 [3]
Rx antenna gain	132.2 dB	Ø 2.0m
Rx transmission loss	-0.5 dB	8 gold-coated mirrors
Rx coupling loss	-1.7 dB	67% efficiency [4]
Reference transmission	-51.3 dB	Table I in [5]
Total transmission	-51.7 dB	computed

We avoid here giving specific details about realistic QKD Txs and Rxs and simply refer to the experimental work presented in [5]. For this QKD system it has been shown that at a link loss of -51.3 dB it is possible to generation of secure key rate block of 8.2 Mbit in a reasonably short time (1.17 hours). The key size is selected so that finite size effects only marginally reduce of the secure key generation rate.

CHALLENGES AND FUTURE WORKS

We have established that with the presented system design around -50dB of source-to-sink loss could be achieved for GEO uplinks. This is compatible with allowing the distribution of a few Mbits of key material to each connected user in around 1 hour. Therefore, this design constitutes a potential blueprint for achieving global-scale QKD with a single satellite. However, further investigations are needed to confirm the technological feasibility of the design and to consolidate the predicted system performance. Furthermore, the very significant costs entailed by placing a Hubble-class telescope in GEO make this proposal potentially realisable only in a rather long-term perspective.

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IPV6-BASED IOT IN 2025

Latif Ladid

INTRODUCTION

The number of Internet Connected devices will cross the incredible total of 50 billion by 2025, see Fig. 1. The connectivity fabric of IP is used to enable more and more efficient context exchange with a broader range of devices and things. This results in the IoT projected to increase device counts by orders of magnitude over the next few decades, IoT's impact cannot be overstated. Already enabling a rich set of new capabilities in smart cities, smart grid, smart buildings, and smart manufacturing, IoT stands to transform virtually every part of modern life that automation or visibility may improve.

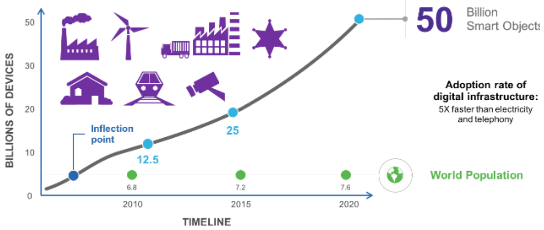

Fig. 1. IoT growth – Source: CISCO

IOT CONNECTIVITY: WIRED AND WIRELESS

No matter the precise forecast, the sheer tsunami of devices coming online in the next months, years, and decades ensures that the future is not exclusively, or even significantly, wired. Wireless with its adaptability and ease will inevitably dominate the IoT landscape. Exactly which wireless technology or technologies will be used remains relatively unclear, as many new technologies are still emerging, while others are still early in the standards process.

The challenges IPv6 poses to high bandwidth wireless networks are well-known. However, low bandwidth links, like LPWAN (Low Power Wide Area Network), do require optimization and broadly adapt and adopt techniques like IPv6 header compression. Clause 4.4 is describing the IETF technologies to adapt IPv6 to different constraint media. This problem is not specific to the use of IPv6 but is due primarily to the scale of IoT deployment.

The following list summarizes the main different wireless technologies used for IoT:

- IEEE 802.15.4 [1] WPAN: The IEEE 802.15 TG4 was chartered to investigate a low data rate solution with multi-month to multi-year battery life and very low complexity. It is operating in an unlicensed, international frequency band. Potential applications are sensors, interactive toys, smart badges, remote controls, and home automation.
- IEEE 802.11 [1]
- WLAN (Wireless Local Area Network).
- LPWAN (Low Power and Wide Area Network).
- Cellular Networks (NB-IoT, 5G).

MOTIVATION FOR IPV6 IN THE IOT

i) Main driver - The main driver is probably the large address space that IPv6 is providing but it is not the only aspect: Auto-configuration, security, and flow identification bring huge advantages to IoT systems as well as being a future-proof technology.

ii) Addressability - Global, public, and private address space have been defined for IPv6; therefore, a decision must be made regarding which type of IPv6 addressing scheme should be used. Global addressing means you should follow the regional Internet registries policies (such as ARIN https://www.arin.net/policy/nrpm.html) to register an IPv6 prefix that is large enough for the expected deployment and its expansion over the coming years. This does not mean the address space allocated to the infrastructure has to be advertised over the Internet allowing any Internet users to reach a given device.

The public prefix can be advertised if representing the entire corporation - or not - and proper filtering mechanisms are in place to block all access to the devices. On the other end, using a private address space means the prefix not be advertised over the Internet, but, in case there is a need for business-to-business services and connectivity, a private address would lead to the deployment of additional networking devices known as IPv6-IPv6 NPT (Network Prefix Translation, IETF RFC 6296 [2]) gateways.

Three methods to set an IPv6 address on an endpoint are available:

- **Manual configuration:** This method is appropriate for headend and NMS servers that never change their address, but is inappropriate for millions of end-points, such as meters, because of the associated operational cost and complexity.

- **Stateless auto configuration:** This mechanism is similar to Appletalk, IPX, and OSI, meaning an IPv6 prefix gets configured on a router interface (interface of any routing device such as a meter in a mesh or PLC AMI network), which is then advertised to nodes attached to the interface. When receiving the prefix at boot time, the node can automatically set up its IPv6 address.

- **Stateful auto configuration:** Through the use of Dynamic Host Control Protocol for IPv6 (DHCPv6) Individual Address Assignment, this method requires DHCPv6 server and relay to be configured in the network. It benefits from strong security because the DHCPv6 process can be coupled with authentication, authorization, and accounting, plus the population of domain name system available for headend and NMS applications.

iii) Security mechanism - In the past, it was sometimes claimed that the use of open standards and protocols may itself represent a security issue, but this is overcome by the largest possible community effort, knowledge database, and solutions available for monitoring, analysing, and fixing flaws and threats - something a proprietary system could never achieve.

iv) IP up to the end device/end to end principle - The past two decades, with the transition of protocols such as systems network architecture, Appletalk, DECnet, Internetwork Packet Exchange (IPX), and X.25, showed us that such gateways were viable options only during transition periods with smaller, single-application networks. But proprietary protocol and translation gateways suffer from well-known severe issues, such as high CAPEX and OPEX, along with significant technical limitations, including lack of end-to-end capabilities in terms of QoS, fast recovery consistency, single points of failure (unless implementing complex stateful failover mechanisms), limiting factors in terms of innovation (forcing to least common denominator), lack of scalability, vulnerability to security attacks, and more. Therefore, using IPv6 end to end (that is, IP running on each and every device in the network) will be, in many ways, a much superior approach for multiservice IoT networks. See IETF RFC 3027 [2] as an example of protocol complications with translation gateways.

CONCLUSIONS

IPv6 can enable and sustain the growth rate of the IoT. It offers a future-proof solution. More and more standardization development organization have decided to either transition to IPv6 or to develop new standards only based on IPv6. This is specifically the case for IoT-related standards. 3GPP secretary and CTO of ETSI Adrian Scrase has already announced back in April 2019 the move from E.164 for machine type communication to IPv6 addressing for larger-scale deployment of IoT. IPv6 does not only enable the scalability required by the IoT but also provides enhancement from IPv4 in the field of mobility support, stateless address auto-configuration, support of constraint devices, and security to mention only a few of them.

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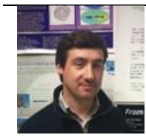

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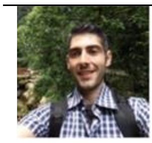

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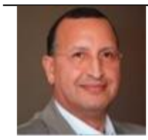

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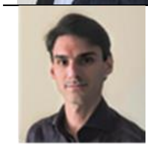

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Acronym

3D	Three Dimensions
3GPP	Third Generation Partnership Project
5G	Fifth Generation
6G	Sixth Generation
A2G	Air-to-Ground
AI	Artificial Intelligent
ANN	Artificial Neural Networks
AP	Access Point
APD	Avalanche Photodiode
ASI	Atmospheric State Information
AUV	Autonomous Underwater Vehicle
AWGN	additive White Gaussian Noise
B5G	Beyond 5G
BER	Bit Error Rate
CSK	Colour Shift Keying
CV	Continuous Variable
DM	Directly Modulated
DV	Discrete Variable
EDFA	Erbium Doped Fiber Amplifier
EDRS	European Data Relay System
eMBB	Enhanced Mobile Broadband
EON	Electro Optical Neurons
ESA	European Space Agency
FSK	Frequency Shift Keying
FSO	Free Space Optical
G2A	Ground-to-Air
GEO	Geostationary
GPS	Global Positioning Systems
GS	Global Shutter
HAP	High Altitude Platform
ICL	Interband Cascade Laser
IM/DD	Intensity Modulation/Direct Detection
IMD	Intermodulation Distortions
IR	Infrared
IRC	Infrared Communications
ISI	Intersymbol Interference
IST	Intelligent Transportation Systems
ITU	International Telecommunication Union
JAXA	Japanese SpaceAagency
JCS	Joint Communication and Sensing
KPI	Key Performance Indicator
LC	Light Communication
LD	Laser Diode
LED	Light Emitting Diode
LEO	Low Earth Orbit
LiFi	Light- Fidelity
LLCD	Lunar Laser Communications Demonstration
LoS	Line-of-Sight
LWIR	Long-wave Infrared
LWIR	Long-wave Infrared
MAC	Medium Access Control
MEO	Medium Earth Orbit
MG-OWC	Multi-gigabit Optical Wireless Communication
MI	Magneto Inductive
MIMO	Multiple-Input and Multiple-Output
MIR	Mid-infrared
ML	Machine Learning
mMTC	massive machine-type communications
mmWave	Millimetre-Wave
MWIR	Mid-wave Infrared

MWIR	Mid-wave Infrared
NE	Neuromorphic Engineering
NS	Neuromorphic Sensors
NS	Neuromorphic Sensors
OA	Optical Axon
OF	Optical Frontends
OFDM	Orthogonal Frequency Division Multiplexing
OGS	Optical Ground Stations
ONN	Optical Neural Network
OOK	On-Off-Keying
OPEX	Operational Expenditure
OSI	Open Systems Interconnect
OU	Onboard Unit
OW	Optical Wireless
OWC	Optical Wireless Communication
P2M	Point-to-Multipoint
P2P	Point-to-Point
PAM	Pulse Amplitude Modulation
PD	Photodiode
PEAQ	Perceptive Evaluation of Audio Quality
PESQ	Perceptual Evaluation of Speech Quality
PHY	Physical Layer
PLC	Powerline Communication
PLS	Physical Layer Security
PM	Prepare-and-Measure
PNN	Photonic Neural Networks
PPM	Pulse Position Modulation
PSM	Photosensitive Material
QBER	Quantum Bit Error Rate
QC	Quantum Communications
QCKA	Quantum Conference Key Agreement
QCL	Quantum Cascade Lasers
QKD	Quantum Key Distribution
RF	Radio Frequency
RGB	Red, Green, Blue
RS	Rolling Shutter
RSI	Road Side Infrastructure
RSS	Received Signal Strength
RU	Roadside Unit
Rx	Receiver
SINAD	Signal-to-Noise and Distortion
SLM	Spatial Light Modulator
SLPT	Simultaneous Lightwave and Power Transfer
SM	Spatial Modulation
SNR	Signal-to-Noise Ratio
SNs	Spiking Neurons
SNSPD	Superconducting Nanowire Single Photon Detector
SPAD	Single-photon Avalanche Diode
SPDC	Spontaneous Parametric Down Conversion
SWaP	Size, Weight and Power
TBIRD	TeraByte InfraRed Delivery
THD	Total Harmonic Distortions
THz	Terahertz
TRL	Technology Readiness Level
Tx	Transmitter
UAV	Unmanned Aerial Vehicles
ULBC	Ultra-reliable Low-latency Broadband Communications
uMBB	Ubiquitous Mobile Broad-band
UOWC	Underwater OWC
URLLC	Ultra-reliable Low-latency Communications
UVC	Ultra-Violet Communications
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle

V2X	Vehicle-to-Everything
ViSQOL	Virtual Speech Quality Objective Listener
VL	Visible Light
VLC	Visible Light Communications
WDM	Wavelength Division Multiplexing
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
WSN	Wireless Specialty Networks
WSS	Wavelength Selective Switches

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