2023 Roadmap on Optical Wireless Communications

Coordinators: Alexis Dowhuszko (Aalto University, FI), Panagiotis Diamantoulakis (Aristotle University in Thessaloniki, GR), and Iman Tavakkolnia (University of Strathclyde, UK).

Collaborators:

- **Cluster 1:** Luis Rodrigues & Luis Nero Alves (Universidade de Aveiro, Portugal); Dini Pratiwi & Lorenzo Gilli & Giulio Cossu & Ernesto Ciaramella (Scuola Superiore Sant'Anna, Italy).
- **Cluster 2:** Xiaodan Pang (KTH, Sweden); Rafael Puerta (Ericsson, Sweden); Nobby Stevens & Jorik De Bruycker (KU Leuven, Belgium); Shenjie Huang & Majid Safari (University of Edinburgh, UK).
- **Cluster 3:** Erdal Panayirci (Kadir Has University, Turkey); Edvin Skaljo (University of Sarajevo & BH Telecom, Bosnia and Herzegovina); Rida Zia-ul-Mustafa & Hoa Le-Minh & Zabih Ghassemlooy (Northumbria University, UK); Carlos Guerra-Yanez & Stanislav Zvanovec (Czech Technical University at Prague, Czech Republic).
- **Cluster 4:** Amita Shrestha (DLR, Germany); Bastien Béchadergue (University of Versailles Saint-Quentin, France); Volker Jungnickel (Fraunhofer HHI, Germany).
- **Cluster 5:** Murat Uysal (Ozyegin University, Turkey); Milica Petkovic (UNS-FTN, Serbia); Valeria Loscri (Inria, France).
- **Cluster 6:** Alessandro Romano & Anna Maria Vegni (Roma Tre University, Italy); Julio Rufo (Universidad de La Laguna, Spain); Maximo Morales Cespedes (Universidad Carlos III de Madrid, Spain); Ikenna Chinazaekpere Ijeh (Alex Ekwueme Federal University, Nigeria); M. Ali Khalighi (Centrale Marseille & Institut Fresnel, France).

Introduction

The NEWFOCUS roadmap provide strategic support and long-term planning for the development of the technologies that are relevant for optical wireless communications (OWC), matching short-term and long-term goals with specific solutions that these technologies may provide. Developing a common roadmap on OWC has three major uses, namely:

1. Assisting in reaching a consensus on a set of requirements and the technologies needed to meet them, particularly when applying OWC to different use cases or applications.
2. Providing a mechanism for more accurate forecasting technology developments.
3. Providing a framework for planning and coordinating the development of technology.

The strategic plan for the preparation of a common roadmap for COST Action CA19111 NEWFOCUS was presented during the 7th Working Group (WG) meeting, held on 20-21 February 2023 in Valencia, Spain. An initial proposal by the three roadmap coordinators was to focus on an industrial roadmap based on six key applications/use cases/scenarios that had been identified within the context of the technology, in which standardization activities have already begun and are expected to significantly impact the use of OWC within a relatively short time frame. These six scenarios were divided into two groups, based on the kind of light source that was dominant:

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1. **Laser-based communications** or free space optical (FSO) links - Which was proposed to be divided into space and aerial applications, underwater communications, and optical “wireless” fibre.
2. **Light emitting diode (LED)-based communications** or visible light communications (VLC) links - Which was proposed to be divided into local wireless access (IEEE-based standardization), mobile cellular communications (3GPP-based standardization), health-care applications and medical use cases.

During the NEWFOCUS meeting held in Valencia, extensive discussion led to the consensus that not only should the workplan reflect the industrial activities that have contributed to the massive adoption of OWC technology, but also the academic contributions that may not have an immediate impact on the industry. In addition, it was agreed that the OWC roadmap should include a structure that encompasses social, economic, and environmental impacts. Following the discussion, it was agreed that the NEWFOCUS roadmap would be divided into six different sections based on the same cluster structure outlined in Horizon Europe programme to address the specific objectives of EU research and innovation grants provided by the European Commission (EC).

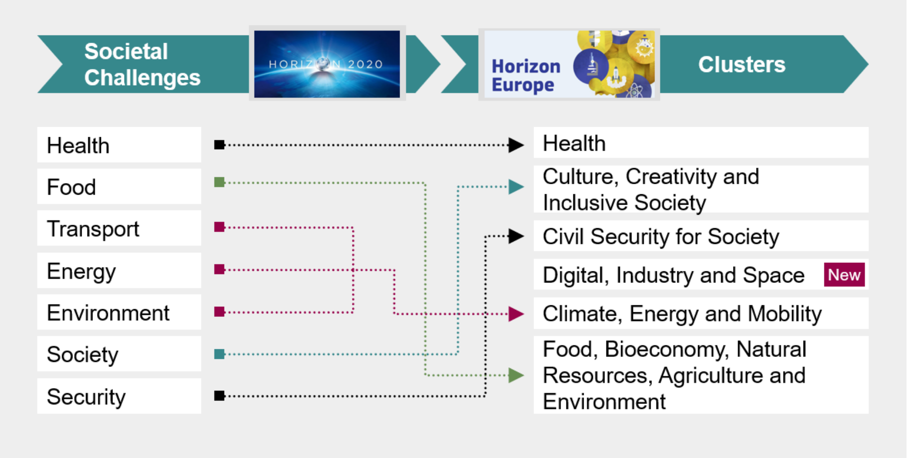
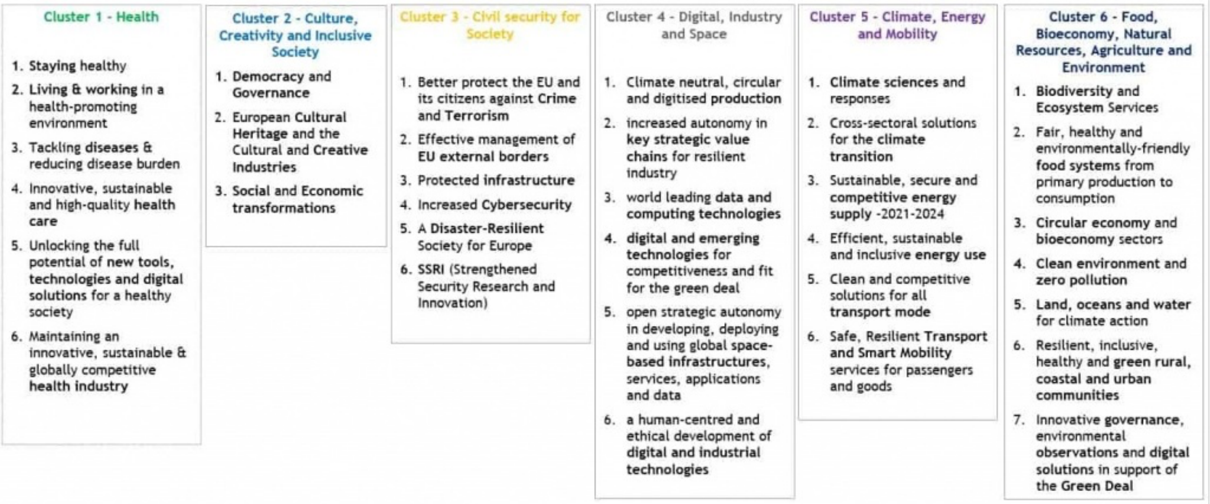


***Fig. 1:** In Horizon 2020 there were 7 Societal Challenges under “Pillar 3: Societal Challenges”. In Horizon Europe these societal challenges are embedded in 6 clusters under “Pillar 2:* Global Challenges and European Industrial Competitiveness*”.*

Cluster areas are listed in Fig. 1 and are further divided into subcategories, as shown in Fig. 2, which are focus areas under the Horizon Europe programme referred to as Destinations.



Cluster 1 - Health	Cluster 2 - Culture, Creativity and Inclusive Society	Cluster 3 - Civil security for Society	Cluster 4 - Digital, Industry and Space	Cluster 5 - Climate, Energy and Mobility	Cluster 6 - Food, Bioeconomy, Natural Resources, Agriculture and Environment
1. Staying healthy 2. Living & working in a health-promoting environment 3. Tackling diseases & reducing disease burden 4. Innovative, sustainable and high-quality health care 5. Unlocking the full potential of new tools, technologies and digital solutions for a healthy society 6. Maintaining an innovative, sustainable & globally competitive health industry	1. Democracy and Governance 2. European Cultural Heritage and the Cultural and Creative Industries 3. Social and Economic transformations	1. Better protect the EU and its citizens against Crime and Terrorism 2. Effective management of EU external borders 3. Protected infrastructure 4. Increased Cybersecurity 5. A Disaster-Resilient Society for Europe 6. SSRI (Strengthened Security Research and Innovation)	1. Climate neutral, circular and digitised production 2. increased autonomy in key strategic value chains for resilient industry 3. world leading data and computing technologies 4. digital and emerging technologies for competitiveness and fit for the green deal 5. open strategic autonomy in developing, deploying and using global space-based infrastructures, services, applications and data 6. a human-centred and ethical development of digital and industrial technologies	1. Climate sciences and responses 2. Cross-sectoral solutions for the climate transition 3. Sustainable, secure and competitive energy supply -2021-2024 4. Efficient, sustainable and inclusive energy use 5. Clean and competitive solutions for all transport mode 6. Safe, Resilient Transport and Smart Mobility services for passengers and goods	1. Biodiversity and Ecosystem Services 2. Fair, healthy and environmentally-friendly food systems from primary production to consumption 3. Circular economy and bioeconomy sectors 4. Clean environment and zero pollution 5. Land, oceans and water for climate action 6. Resilient, inclusive, healthy and green rural, coastal and urban communities 7. Innovative governance, environmental observations and digital solutions in support of the Green Deal

***Fig. 2.** Each of the six Clusters entails further sub-categories, focus areas, or so-called Destinations.*

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Cluster 1: Health

Research and innovation actions under this cluster will be key to address health-related challenges by advancing knowledge and capabilities, improving understanding of health and diseases, and developing innovative methodological and technological solutions to better manage health and diseases. The design of sustainable approaches for the digital transformation and delivery of integrated, person-centred and equitable health and care services will be also considered.

In this context, two use cases have been identified in which OWC would have a key role within the activities of this cluster, namely:

- OWC for healthcare services
- Transmitting healthcare signals with optical wireless technology.

1.1 OWC for healthcare services

Status. Health care sensors market is a fast-growing market projected to reach 3 billion USD by 2026 at a growing rate of 10.3%. Several factors justify this growing rate, but most importantly, the increasing adoption of sensors in portable medical devices, the growing elderly population and the increase of life expectancy, and the rising demand for wearable and implantable medical devices, are the factors that drive this growing market. Communications with wearable and implantable medical devices can be broadly classified in two categories: the intra wireless body arear network (WBAN) and the extra WBAN. Intra WBAN devices have a limited communication reach, extending up to 1 meter, mainly accomplishing the communication of sensors in the patient body with a concentrator node (CN). Extra WBAN refers to the communication between CN and the external network Access point (AP) and it extends up to 10 meters. In terms of bandwidth requirements, medical devices must comply with a bandwidth in the range of 10 kbps to 10 Mbps depending on the specificity of the application. WBANs are designed to satisfy bit error rates (BER) in the range of 10^{-3} for deep brain stimulation to 10^{-9} for electroencephalogram (EEG) recording. Also, the required latency for medical applications should be lower than 125 ms **[C1.1]**. WBAN are used with two main proposes, continuous monitoring of vital signs such as electrocardiogram (ECG), EEG, electromyogram, blood glucose levels, blood pressure, heart rate, motion and pose, amongst others); and therapeutic stimulation (trough the delivery of drugs or stimulus). Indicatively, more details about the monitoring of ECG signals using optical wireless technology, which is a mature technology, are given in the next subsection. Current WBAN technologies are dominated by radio solutions, most notably, Bluetooth and Zigbee operating in the ISM band. These popular radio solutions and their variants comply with low complexity and low energy requirements, which are common architectural requirements for this type of sensor.

Current and future challenges. Radio-based solutions dominate the WBAN market, nevertheless they have some drawbacks. Radio based solutions are not exempt from electromagnetic interference which is a major drawback in medical facilities where interference with medical equipment cannot be tolerated. Radio-based solutions face stringent bandwidth regulations, which may limit the number of communication devices. Also, radio-based solutions are prone to eavesdropping which compromises security. OWC appear as a good candidate to complement the radio-based solutions. OWC is able to offer energy efficiency, immunity to electromagnetic interference, a large bandwidth free of licensing and increase security (as light is confined to spaces). OWC solutions also face some challenges that prevent their full adoption as a viable technology. The major challenges that are currently under investigation are: i) the availability of adequate channel models for intra WBAN devices – due to motion of the patients or the allocation of sensor devices to different parts of the body of the patients, the availability of direct links is usually compromised. The OWC channel for these devices has to rely on non-line-of-sight (LoS) configurations. The possibility of patients' movement also implies the channel is time dependent.; ii) Due to the existence of multiple sensing devices, the network topology should support multiple access (MA) to the channel. Different solutions exploring code division MA (CDMA), orthogonal frequency division MA (OFDMA) and multi-band carrier-less amplitude and phase modulation (m-CAP) are currently receiving research attention; iii) Complexity and power consumption of the sensing devices. Network APs have no constraints on power and complexity. However, this is not the case of sensing devices, which should exhibit low power consumption (implantable devices should include energy harvesting capabilities), low complexity and reduced form factors. Combining these stringent requirements with the complexity of MA techniques is an ongoing challenge; and iv) Finally, addressing the communication with implantable devices. This entails communication through the skin and body tissues, a medium which severely constraints communication reach.

Advances in science and technology to meet challenges. Current research is WBAN scenarios is focusing on the challenges previously identified in different fronts. Concerning the channel models for intra WBAN devices, the authors in **[C1.2]** analyzed the viability of communications in a realist body movement scenario. The study recurred to a three-dimensional walk cycle animation model and Monte Carlo raytracing to estimate the channel at different instants in time. The study proposed a statistical model for the channel DC gain, delay spread and coherence time that best fits the simulation results. Concerning multiple access, current research is focusing on the usage of different MA techniques. In **[C1.3]** optical CDMA is investigated and the MA scheme for communication between the concentrator node in the patients' body and the AP in the ceiling, using an infrared (IR) carrier. The performance is investigated in terms of achievable BER and outage probabilities. In **[C1.4]** the authors focus on the usage of optical OFDMA as MA scheme. The study proposes the transmission of the real value components of the OFDM stream to remove the Hermitian symmetry and reduce the complexity. The achieved performance demonstrates that it is possible to reduce power consumption by 35 mW for a BER of 10^{-3} when compared to conventional OFDM. The authors in **[C1.5]** addressed the problem of MA and complexity of the sensing devices. The study proposes the usage of m-CAP, a modulation technique that supports MA, to reduce the complexity of the sensing devices. The achieved results show that it is possible, resorting to analog circuit design, to recover a single carrier from the m-CAP signal thus alleviating the need to dedicated signal processing means at the receiving devices. Concerning the communication with implantable devices using OWC means, the study in **[C1.6]** and references therein show that it is possible to simultaneously communicate and harvest energy from the optical carrier, using communicating devices implanted under the skin.

Concluding remarks. OWC offers interesting opportunities to communicate with devices in WBAN scenarios, involving healthcare facilities. These opportunities are not exempt from challenges which are currently being addressed. The research field is mature and very fertile, novel strategies and novel devices will emerge offering improved performance and the ability to cope with the stringent requirement posed by sensing devices.

1.2 Transmitting healthcare signals with optical wireless technology

Status. Medical technology is essential for the monitoring of health information of patients **[C1.7]**. However, the cabling in medical devices designed for health monitoring can interfere with the operation process and nursing **[C1.8]**. To address this issue, medical devices using radio frequency (RF) wireless technology has been proposed as an alternative. However, RF radiation has some drawbacks, including low electromagnetic compatibility with other wireless devices and potential harm to patient health due to long-term exposure to RF radiation **[C1.9]**.

Current and future challenges. Recently, researchers have suggested to exploit the VLC as a solution of the problem of electromagnetic interference **[C1.10]**. ECG transmission using VLC in LOS configuration within a distance of 50 cm has been performed to provide the heart rate data of the

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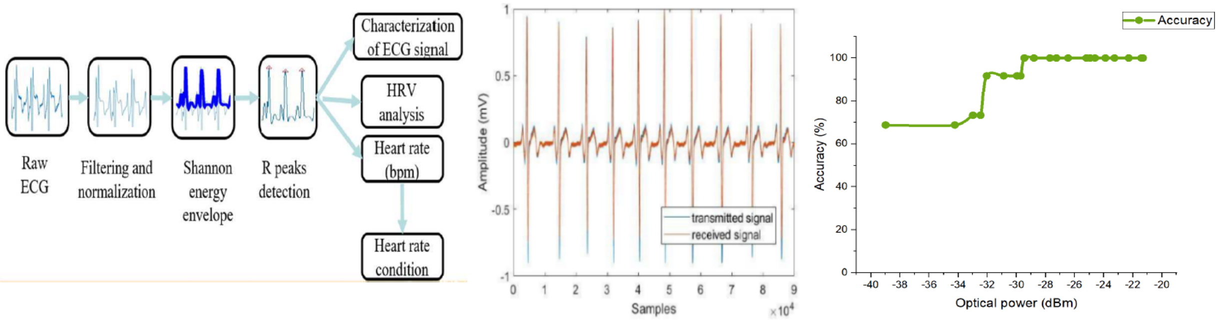
patient **[C1.11]**. Additionally, visible light-based optical camera communication (VL-OCC) has been demonstrated as another approach to transmit medical data. Several research in ECG signal transmission using OWC has been introduced. However, biomedical characterization of the OWC systems transmitting ECG signals has not been performed and this is crucial for medical purposes to analyse the heart rate. Generally, ECG signals are often corrupted by various source of noise, and these artifacts can negatively impact the accuracy of the R peaks detection and heart rate variability (HRV) analysis. A noiseless ECG signal is required to achieve a reliable and accurate diagnosis of heart rate conditions.

Advances in science and technology to meet challenges. We designed a solution that utilizes OWC to transmit directly analog ECG waveforms. Our experiment demonstrated that optical antennas are able to transmit with high accuracy at a 1 m transmission distance in a LOS configuration. To evaluate the performance of the system, we performed a quantitative characterization of the ECG signal at the receiver-end (Fig. 1.1.a) and processed the received ECG signal using digital signal processing to obtain HRV and heart rate information (Fig. 1.1.b). We compared HRV values in transmitted signals to those received to evaluate the performance of the OWC system. We also measured the sensitivity of the receiver to determine the minimum optical power required for the system to have good accuracy. Ultimately, we evaluated the accuracy of the solution for medical applications. The experiment results show a minimum optical power of -30 dBm was needed to achieve an accuracy of 92% (Fig. 1.1.c). By transmitting the analog ECG signals directly, we avoided the need for any analog-to-digital converter (ADC) and digital-to-analog converter (DAC), making the system less complex and more suitable for medical applications in hospitals.

Concluding remarks. This preliminary experiment proves the feasibility of analogue ECG signal transmission using VLC. However, the current architecture it is not suitable for users who need mobility, because the transmitter and the receiver must have a fixed position to obtain direct sight in LOS configuration. Additionally, if any obstacles are present between the transmitter and the receiver, the transmission cannot be guaranteed. Therefore, further optimization and improvement will be required to achieve a good degree for user mobility. As an example, improved performance can be achieved by optimizing the transmitter and receiver devices.



a) Block diagram b) ECG signals c) RX sensitivity

Fig. 1.1: *a) Digital signal processing for the characterization of an electrocardiogram; b) Illustration of the transmitted and received ECG signals that are obtained; and c) Measurement of the receiver sensitivity.*

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Cluster 2: Culture, creativity, and inclusive society

Research and innovation actions under this cluster will address EU priorities that give a new push to European democracy, supporting an economy that works for people. The European Green Deal, making Europe fit for the digital age, protecting European way of life, making Europe stronger in the world, are also objectives of this cluster. A better management of migration and mobility, while protecting our cultural heritage and stimulate creativity, are also ambitions to be addressed here. Cluster 2 will also address the unprecedented societal consequences of the COVID-19 pandemic and will mobilise European social sciences and humanities research for providing evidence bases that enable policies helping recovery and enhancing resilience and responsiveness in case of future crises.

In this context, three use cases have been identified in which optical wireless communication would have a key role within the activities of this cluster, namely:

- Optical wireless communications for indoor access
- Indoor positioning based on optical wireless technologies
- Mobile fronthauling over optical wireless links for ultra-densification

2.1 OWC for indoor access

Status. OWC refer to the transmission of data using unguided light. In recent decades, extensive research efforts have been devoted to the research of OWC, which accelerate its commercialization progress. We are currently in an unprecedented era, where the emergence and evolution of smart products, interactive services and intelligent applications happen in an expeditious manner, leading to a high demand for wireless communications. According to Ericsson, the global mobile traffic reached around 90 exabytes per month by the end of 2022 and is projected to increase to 325 exabytes per month by the end of 2028. Due to the congestion of the current RF spectrum, OWC with its additional bandwidth and high-security level features is envisioned to play a vital role in future wireless connectivity, especially indoors. OWC will also be crucial for enabling technologies such as metaverse, virtual reality and augmented reality, which can have transformative impacts on the culture and society. Finally, as an energy-efficient and low-cost technology, OWC can contribute to the sustainability of digital infrastructure and help to reduce the carbon footprint of the telecom sector.

Current and future challenges. Despite the extensive research of OWC over the last decades, commercialization of this technology still faces numerous challenges. Although the optical spectrum is many orders of magnitude larger than the whole RF spectrum, the speed of the current OWC systems is strongly limited by the bandwidth and nonlinearity of transceivers, particularly for systems employing LEDs at the transmitter side. Additionally, due to the highly directional and narrow beamwidth of light sources, OWC relies on the existence of LoS propagation between transmitter and receiver for achieving a reliable data rate performance. As a result, it is susceptible to service outages induced by various channel impairments, for example, user mobility, blocking, and dimming control in indoor applications **[C2.1]**. Developing resilient OWC systems by addressing these impairments, while maintaining high-speed transmission, is a formidable challenge. For example, seamless ultra-high-speed light communications networking for indoor environments requires careful mobility support in the presence of blockages and misalignment issues.

Advances in science and technology to meet challenges. New materials and devices are desired in OWC to solve the transceiver bandwidth limitation and nonlinearity issues. For instance, in recent years, research groups have focused on proposing novel wide-bandwidth light sources for OWC, such as micro-LEDs and Organic LEDs (OLEDs) **[C2.2]**. However, these new light sources have their limitations, such as low transmission power and high cost. Therefore, more research efforts should be devoted to this regard. To overcome channel impairments in OWC, numerous studies have been conducted, especially for indoor applications. Technologies such as beam-steering, Intelligent reflecting surfaces (IRS), multiple-input multiple-output (MIMO), and wide-field-of-view imaging receivers, have been investigated to improve the throughput, and support mobility **[C2.3, C2.4]**. Moreover, recent advancements in machine learning (ML) techniques present exciting potential to enhance the performance of OWC and address its formidable challenges. These techniques can be applied in various aspects of OWC, including nonlinearity compensation, channel estimation, and modulation format identification.

Concluding remarks. The congestion of the RF spectrum has led to an increased interest in exploring the optical spectrum for communication purposes. OWC offers several advantages which make it a promising technology for future wireless networks. While OWC has recently received considerable attention from both industry and research communities, many challenges still hinder its widespread commercialization. In this section, the status, potential challenges, and some available techniques to address them are summarized when used to provide optical wireless access indoors. It can be anticipated that more rapid deployment of OWC technology in our daily lives is feasible if the challenges associated with its implementation can be successfully overcome.

2.2 Indoor positioning based on optical wireless technologies

Status. Reliable indoor positioning and tracking has been a longstanding challenge as it is an essential requirement for various applications such as factory automation, robot navigation, asset tracking, among others. In this context, OWC-based positioning has proven to be an accurate and precise means of providing indoor localization. A substantial number of positioning methods have already been investigated in the context of OWC-based positioning systems **[C2.5, C2.6]**, of which the vast majority employs the received signal strength to perform a position estimation. On one hand, these methods employ multi-lateration based on estimated distance, derived from optical channel models, often assuming Lambertian radiation patterns. On the other hand, several data-driven approaches exist ranging from fingerprinting methods to ML and artificial intelligence (AI) assisted regression models **[C2.7]**. Additionally, other approaches also make use of angle of arrival techniques employing photodiode arrays with apertures. Furthermore, time-based methods have also been investigated, though solely in theory and simulation **[C2.8]**, practical implementations have yet to be realized. The above mentioned OWC-based positioning methods have proven to achieve sub-10-cm accuracies in practical applications such as the one illustrated in Fig. 2.1, yet room for improvement remains. Further advancing existing positioning methods and investigation of time-based methods can increase the robustness and performance of OWC-based positioning systems to better support existing and future demand for reliable indoor navigation and as an enabler for a multitude of location-based services.

Fig. 2.1: *Sample experimental setup with four transmitting LEDs and close-up of the custom photodiode-based receiver.*

Current and future challenges. The performance of the previously mentioned OWC-based positioning methods still faces several distinct challenges. As previously mentioned, the vast majority of practically used methods employ received signal strength as a parameter for the position estimation. This received signal strength is however very susceptible to numerous fluctuations, causing a detrimental effect on the performance of the applied positioning methods. In practice, these fluctuations and the quite often assumed Lambertian channel model can lead to considerable positioning errors due to deviations in the radiation pattern **[C2.9]**, installation inaccuracies, receiver tilt, dust accumulation, LED aging, among others. Several solutions already exist to cope with these fluctuations to a certain extent, and while certain data-driven approaches provide an elegant solution, the impact of receiver tilt on one hand, and received signal strength variations caused by dust accumulation and LED aging remain as persistent challenges.

Advances in science and technology to meet challenges. Time-based positioning methods should be further investigated and advanced from purely theoretical and simulation-based studies, as well as applied and tested in practical implementations. As the time-of-flight is inherently independent of several impacting factors on the received signal strength, the detrimental effect on the performance limiting previously investigated methods is completely resolved. Experimental setups should be constructed to assess the performance regarding precision and accuracy of time-based OWC-based Positioning and to gauge this performance in comparison to previously established positioning methods. Additionally, the joint knowledge of both received signal strength and timing information can be leveraged to improve and surpass the performance of either method separately.

Concluding remarks. OWC-based positioning has presently demonstrated to achieve adequate results indoors. Several outstanding challenges however remain to be solved to improve the reliability, usability, and performance of OWC-based positioning systems in indoor environments. Quite certainly, further examination of existing positioning methods and commitment to time-based methods can break the glass ceiling as imposed by current systems.

2.3 Mobile fronthauling over optical wireless links for ultra-densification

Status. The Key Performance Indicators (KPIs) of 5G for download and upload speeds are 100 Mbps and 50 Mbps **[C2.10]**, respectively, which are substantially lower than the long-term requirements for emerging applications such as extended reality and digital twins. Thus, a new solution for higher data rates and ubiquitous service is needed for Beyond 5G (B5G) mobile networks. Foreseen requirements and use cases have shown that current mobile network implementations must be reconsidered. In cases where large bandwidth signals and low complexity radio units are necessary, current digital fronthaul interfaces, such as the Common Public Radio Interface (CPRI) and the enhanced CPRI (eCPRI), face complications due to their limited spectral efficiency and flexibility.

Free space optical (FSO) links, even though they have been proposed, studied, and even developed since decades ago, have not yet been considered by operators as reliable building blocks for the current terrestrial ICT infrastructure. Most commercial FSO solutions today are built upon existing transceiver technologies developed for fibre-optic telecom applications operating at near infrared (NIR, 0.8-2 µm) bands. There have been many lab demonstrations or field trials of various FSO systems, yet they are commercially used only in some corner cases. However, increased attention and discussions around FSO and its application in supporting specific application scenarios in the scope of the current and next generations of radio access networks, specifically for 5G and B5G mobile fronthaul, have emerged recently **[C2.11]**.

Current and future challenges. Envisioned challenges in mobile fronthaul include but are not limited to: 1) scalability in terms of data rate; and 2) deployment cost for a large number of fronthaul links if only optical fibres were considered. For FSO technologies, the most significant challenge is to address the link availability issue against different weather conditions.

Table 2.1. *The scaling of CPRI-like interfaces* ***[C2.12]****.*

Number of Antenna Ports	*Frequency System Bandwidth*		
	20 MHz	*200 MHz*	*1 GHz*
2	*2 Gbps*	*20 Gbps*	*100 Gbps*
8	*8 Gbps*	*80 Gbps*	*400 Gbps*
64	*64 Gbps*	*640 Gbps*	*3200 Gbps*
256	*256 Gbps*	*2560 Gbps*	*12800 Gbps*

Table 2.1 presents the data rate scaling challenges of CPRI-like interfaces concerning the number of antenna ports. As one can see and extrapolate from the table, scalability in the long term imposes great challenges following the existing digital solutions. Similar tendencies hold for different function-splitting variants of CPRI, such as eCPRI, with different trade-offs. Among the many enablers of B5G and 6G mobile networks, MIMO technology continues to play a key role. Today, MIMO systems still underperform compared to the theoretical channel capacity bounds. Thus, innovative approaches are critical to bridge this gap, especially in case of distributed MIMO **[C2.13]**. A large number of fronthaul links are expected to support such a scenario.

Regarding FSO systems running at NIR, which is the telecom band, the main challenge comes from the atmospheric channel. FSO channel operating at NIR wavelength is susceptible to atmospheric perturbations, namely: scattering by aerosols such as dust, haze, fogs, and clouds, as well as turbulence effects such as scintillation, beam broadening, and beam wandering, which hinders the applications of FSO in most long-distance (i.e., d > 1 km) terrestrial scenarios.

Advances in science and technology to meet challenges. To address the scalability challenge regarding speed and user count, an analogue optical interface directly modulates wireless signals on the optical carrier to eliminate data rate scaling problems in CPRI-like interfaces. Such analogue solutions can be configured with both fibre optics and FSO. Secondly, FSO systems with fast installation and an upgrade pace offer a lower-cost complementary solution to tackle the challenge of deploying massive amounts of fronthaul links, particularly in ultra-densely populated areas or geographically prohibiting areas for fibre deployment. Moreover, the potentially seamless and versatile integration of the FSO systems with existing fibre-optic systems and networks is also straightforward and viable. Lastly, the progress in solid-state semiconductor transceiver technologies for the mid-IR FSO, including two transparent atmospheric windows, namely, the Mid-Wave IR (MWIR, 3-5 µm) and Long-wave IR (LWIR, 8-12 µm), can be promising. Longer wavelength FSO links have extremely low sensitivity to turbulence (proportional to λ^{-a}, with $-a \geq 1$) and scattering by aerosols or droplets; thus, atmosphere can remain highly transparent with a much longer range and in far worse conditions than the NIR telecom band. Recent breakthroughs in unipolar quantum cascade semiconductor devices, including Quantum cascade lasers, quantum cascade detectors, and external Stark-effect modulators that operate at room temperature with high bandwidth and satisfying noise performance, have facilitated a series of high-speed FSO system demonstrations. Recently, 5G new radio (NR) conformance testing of analogue radio-over-long-wave-IR (LWIR) FSO fronthaul link based on directly modulated QCL has yielded promising results **[C2-14]**.

Concluding remarks. Several challenges are identified following the roadmap of conventional digital-based mobile fronthaul technologies for RAN, including data rate scalability and the requirement of massive links. FSO technologies provide a relatively low-cost and fast upgrading alternative to complement the existing fibre-optic systems, yet the link availability issue requires a solution. Adopting longer wavelengths in the mid-IR region appears to be a potential candidate enabled by recent progress in quantum cascade semiconductor technologies.

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Cluster 3: Civil security for society

Research and innovation actions under this cluster will address challenges related to the protection and resilience of physical and digital infrastructures, as well as of vital societal function. Disasters, whether natural or man-made, call for better preparation to prevent and reduce the loss of life, harm to health and the environment, economic and material damage as well as to improve the understanding and reduction of disaster risks and post-disaster lesson learning. Climate change is likely to exacerbate security challenges outside of disaster events, and lessons need to be learnt from the COVID-19 crisis both in terms of preparedness and capacity building for crises and in improving responses to cross-sectoral aspects of such events.

In this context, three use cases have been identified in which OWC would have a key role within the activities of this cluster, namely:

- Physical Layer Security over optical wireless links
- Optical wireless communications for disaster risk reduction and resilience
- Quantum key distribution over optical wireless links.

3.1 Physical Layer Security over optical wireless links

Status. The exponential growth in data traffic requires a new spectrum in 6G, which will open new THz bands and exploit joint communication and sensing approaches. However, operating under aggressive latency constraints, in massive connectivity regimes, with low energy footprint and low computational effort, while providing explicit security guarantees, can be challenging. Incorporation of physical layer security (PLS) schemes in 6G security protocols, exploiting the characteristics of physical phenomena to provide security, PLS can complement conventional upper-layer security schemes to strengthen overall trust and resilience of 6G.

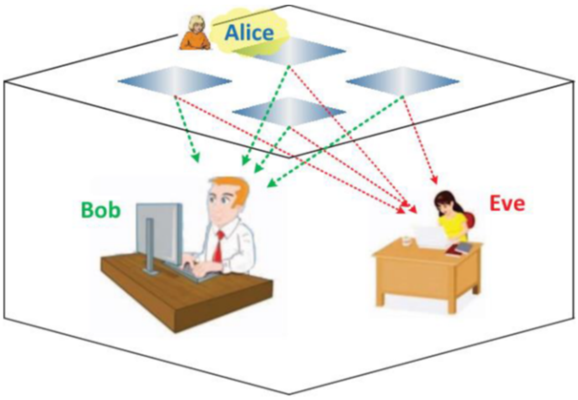

Fig. 3.1: Sample scenario of an indoor OWC single-input single-output scenario aiming at providing PLS.

Besides providing a keyless and secure communication channel via maximization of the secrecy rate, PLS can also exploit the intrinsic characteristics of the wireless channel to co-generate a cryptographic key for symmetric encryption, found in sample indoor scenarios such as the one shown in Fig. 3.1. The physical layer exposes significant vulnerabilities due to the broadcast nature of the wireless channel. It is well known that if the eavesdropper is equipped with sufficient computational power, protocol security can be compromised. Since light does not propagate through opaque objects such as walls and is also very directional, light beams can be formed without the need for excessive signal processing efforts with lenses and other optical components. It is, therefore, possible to significantly reduce the possibilities of man-in-middle attacks in LiFi compared to WiFi **[C3.1]**.

Current and future challenges. Key research issues and challenges in general and optical PLS are:

- Which are the most suitable physical layer features to be exploited for the definition of security algorithms in challenging B5G heterogeneous environments characterized by high network scalability and different forms of active malicious attacks?
- How can artificial intelligence be exploited to tune physical layer security 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 quality of service?
- 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 platform security be ensured with transceivers distributed in different locations?
- How can confidentiality be ensured between the central baseband processing unit and antenna stripes?
- What kind of security mechanisms could be used between the transmitter and the IRS panel and how can the security of the IRS controller be ensured?
- What are the new and novel algorithms that can be designed for PLS in multiuser and broadband VLC systems using new modulation schemes?
- How to incorporate user mobility and device orientation into the VLC channel models and combining VLC and RF systems?
- How to develop computational techniques for the maximum achievable secrecy capacity and secrecy rate of the PLS algorithms in VLC?

Advances in science and technology to meet challenges. The PLS are mostly based on techniques such as precoding, jamming and subset selection, as well as combinations of these techniques. In precoding approaches, widely adopted in most applications due to their simplicity, through the channel state information at the transmitter of the legitimate user **[C3.2-C3.3]**. A well-known method based on generating a friendly jamming signal creates an artificial noise, which lies in the null space of the legitimate user **[C3.4]**. After combining the confidential information with the jamming signal at the transmitter 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. The transmitter subset selection technique is based on choosing a specific subset of transmitting entities according to the radiation patterns of the transmitting units **[C3.5]**. 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.

Concluding remarks. OWC and its potential to solve physical layer security (PLS) issues are becoming important research areas in 6G networks. Although VLC systems are more immune against interference and less susceptible to security vulnerabilities, security issues arise naturally in VLC channels due to their open and broadcasting nature. In addition, since VLC is considered to be an

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enabling technology for B5G, and security is one of its fundamental requirements, and this should be carefully addressed and resolved in the VLC context. Due to the success of PLS in improving the security of RF wireless networks, extending such PLS techniques to VLC systems are of great interest.

3.2 Optical wireless communications for disaster risk reduction and resilience

Status. Cluster 3 of the Horizon program - Civil Security for Society - refers to disaster risk reduction and resilience, which is based on prevention, mitigating consequences, and preparing for and building capacity for crisis situations, in addition to the cross-sectoral aspect of the crisis. Projects consider human factors and the societal context, and they ensure the respect of fundamental rights, such as privacy and data protection. This area of EU interest will build on the lessons learned at COVID-19.

The sensor-required portion of Cluster 3 can benefit from optical wireless **[C3.6-C3.10]**. Thus, during the Covid-19 virus pandemic, optical wireless near-infrared (NIR) technologies played an important role in non-contact temperature measurement. In this context, OWC can be subdivided into three categories, namely: visible, NIR, and far-infrared (FIR) light communications. Each of these categories has recently seen significant use in sensor applications. For example, using high-resolution cameras and artificial intelligence-based software, it is possible to monitor the movement of tens of people and objects in an area the size of a football field. In the NIR region, non-contact temperature sensors are widely used. Human body scanners that work in the *mm*-range are widely used in the FIR area, in the domain of terrorism and smuggling prevention.

Current and future challenges. Because the diffraction of light is directly proportional to the wavelength, the use of electromagnetic waves at visible and infrared wavelengths in sensor applications has the advantage of high accuracy when compared to other non-ionizing electromagnetic waves **[C3.6]**:

$$\sin(\theta) \sim \frac{\lambda}{r}, \text{(3.1)}$$

where *r* is the diameter of the focal mirror or the aperture of the crack. As a result, the use of optical wireless wavelengths enables the application of high-resolution detection, such as detecting a gun on a human body hidden beneath clothing, or signal interception. Because these communication links are characterized by a very narrow point-to-point beam, optical wavelengths enable connections that are more secure in terms of interception/eavesdropping. The optical signal traveling from the light source to the detector is affected by four phenomena: reflection, transmission, absorption, and scattering.

LIDAR technology research can also be used to meet the needs of sensor applications in civil security. Thus, if light monitoring of a park-sized area is desired, it should be noted that plant reflectivity increases at wavelengths ranging from 700 to 1.9 mm, with one window of low reflectivity around 1450 nm, so these wavelengths should be avoided for this application because plants with reflected light will blind the detected return light. Point-to-point beam that is narrow.

Advances in science and technology to meet challenges. Because optical wireless uses non-ionizing wavelengths, it is not dangerous to people except in the human eye, which should be prevented. Thus, visible light and NIR in the near-visible light range can harm eyesight, whereas FIR wavelengths do not.

Light from other sources, which represent noise in optical wireless applications, should also be considered. As a result, the power of sunlight radiation decreases with increasing wavelength and nearly disappears at wavelengths of 1800 nm, with several minimum values, one of which is around 1450 nm. As a result, wavelengths around 1450 nm and above 1900 nm appear to be ideal for space monitoring because they have no effect on human eyes, can see through plants, and have little influence from sunlight.

Civil Security for Society can also use optical fiber technologies operating in the wavelength window of 650 to 1800 nm with a separate low-loss window of wavelengths ranging from 1280 to 1625 nm when obtaining information from hostile/dangerous environments. Sensors can be placed hundreds of kilometers apart and do not require power.

Remote sensing via fiber optic fibers can be used in the control of food production, the detection of weather conditions, the movement of glaciers, the occurrence of avalanches, the search for lost mountaineers, or the monitoring of people's passage along some road passages in remote areas without requiring power or changing batteries. When designing the sensor, care should be taken with the receivers, so that for wavelengths up to 1100 nm, Si can be used, while other materials such as GaInAs, which are significantly more expensive, must be used above this range.

Concluding remark. A significant role for wireless optics is found in civil security. Particularly, it seems that the wavelengths at the transition between NIR and FAR are technically the most amenable to the use of preventive controls in both motion tracking and hidden object detection. It is expected that research into the four sensory phenomena of reflection, transmission, absorption, and scattering will continue. In this field, optical fiber remote sensing has enormous potential. Other than silicon, research into low-cost materials is required.

3.3 Quantum key distribution over optical wireless links

Status. VLC is a promising technology to improve the capacity of the existing indoor wireless communication systems. However, VLC also comes with security concerns in line with other wireless and wired transmission systems. In this regard, one-time pad cipher aided by quantum key distribution at the physical layer has been proposed as an optimal solution to enhance the security of VLC networks.

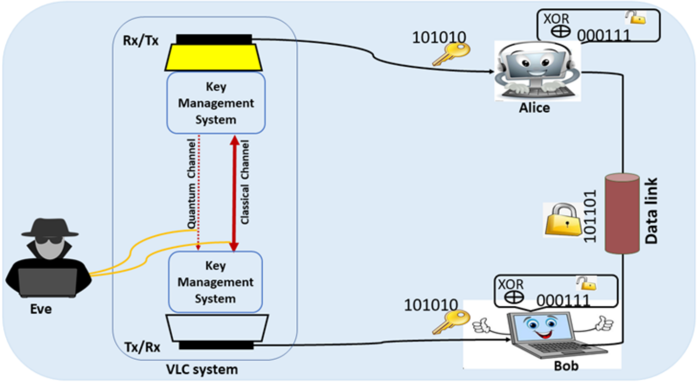

Fig. 3.2: QKD-secured wireless communications system with trusted secret key generating nodes.

Current and future challenges. There are several challenges for the implementation of quantum key distribution (QKD), such as the one shown in Fig. 3.2. Recently, much effort has gone into increasing the data throughput and the transmission range as well as making them low cost, compact, and robust. New software and hardware such as novel protocols and chip-based QKD devices are being investigated and developed in the quest for improved performance and low costs. Protocols such as measurement device-independent (MDI) and loss-tolerant QKD have been developed. However, further research should be conducted focusing on (i) a comprehensive theory of the model of a QKD source; (ii) quantum repeaters; (iii) new applications, such as VLC; (iv) mobile QKD applications in smart devices; and (v) standardization.

In a large part of quantum optics applications such as QKD, a perfect single-photon source is assumed to be used, which is not practical with present technologies. Therefore, weak laser pulses are often used to encode the bitstream. In this implementation, photons may be produced in multi bunches, which produce a vulnerability. The eavesdropper may attack by holding on to one of the photons and passing on the remaining to the receiver (Rx). Following the transmitter’s (Tx’s) announcement on its choice of basis, the eavesdropper can measure the stored photons on the correct basis and completely recover the key. To avoid such an attack, a decoy-state protocol and a decoy method based on only a signal and two decoy states were proposed **[C3.11]**. These states can be the photon intensity, wavelength, polarization, etc. In addition to the availability of many protocols, the security of BB84 - as one of the most promising QKD schemes - is proven in the case where the key information is encoded in the relative phase of a coherent state reference pulse and a weak coherent state signal pulse (continuous phase randomized coherent state). A discrete phase randomized coherent state source offers an improved decoy-state QKD performance by decreasing the number of random bits.

The unconditional security of the BB84 QKD protocol has been strictly proven based on the laws of quantum mechanics. This is the case even when implemented practically with some imperfections such as weak coherent pulses, detector dark counts, and detector efficiency mismatch. However, practical QKD systems have many other shortcomings, where an eavesdropper can exploit them to launch specific attacks, which are not dealt with in the original security scheme. In the above cases, the Tx uses a reference pulse, and since it does not monitor the arrival time of the pulse, the eavesdropper can change the time delay and place its pulse on the rising end to achieve partial pulse modulation without being detected. To remove this attack, MDI-QKD was proposed in **[C3.12]**, which utilized another powerful quantum tool, the Bell test, to check the authenticity of the results.

In addition to the common issues in QKD, there are a few major challenges in the implementation of QKD VLC systems including: improving the key generation rate, increasing the transmission range, reducing the cost, networking, and improving robustness alongside compatibility with the illumination infrastructure of the VLC. Of course, for indoor VLC systems, short-range QKD is not a challenge; however, enhancing the QKD bit rate can be a major issue. Using integrated optics and adopting diverse ways to reduce losses can also help users to increase the bit rate for indoor and outdoor VLC systems. The broad range of challenges faced by QKD-secured wireless networks are stated as follows:

- Account for possible user mobility.
- Reduce the effects of ambient light on the performance of the systems.
- Develop schemes with improved robustness against channel effects and interference.
- Improve the quality of the single photon generation and detection systems.
- Improve the robustness of the practical implementations to side-channel attacks and jamming.

Table 3.1. *QBER and SKR for experimental implemented QKD schemes.*

Ref.	***Implemented scheme***	***Transmission media***	***Distance (km)***	***Achieved QBER (%)***	***Achieved SKR (bps)***
[8]	*BBM92*	*Dusty free space*	*0.2*	*4.5*	$1.71 \cdot 10^3$
[10]	*Decoy state BB84*	*Free space*	*-*	*4.3*	*543*
[16]	*CVQKD*	*Optical fibre*	*a. 5* *b. 10* *c. 25*	*-*	a. 190.54×10^6 b. 137.76×10^6 c. 52.48×10^6
[18]	*BB84-based*	*Free space*	*8.5*	*8.6*	*134*
[19]	*BBM92*	*Optical fibre*	*10*	*6.4*	*109*

Advances in science and technology to meet challenges. To address atmospherical impairments, in **[C3.13]**, the experimental validation of a QKD scheme for FSO over a 200 m dusty channel was reported with the secure key rate and QBER of 1.71 kbps and 4.5 %, respectively. The effects of turbulence on the performance metrics of the hybrid M-ary pulse position modulation (MPPM)/BB84 scheme were theoretically investigated in **[C3.14]**, where the simulation results show that turbulence only affects performance when the system is operating under intense fog conditions. In some theoretical works, it was assumed that turbulence does not affect the link performance, therefore, there is no need to investigate it. However, more recent research has proved that moderate to strong turbulence can deteriorate the performance of free-space QKD links. In **[C3.15]**, it was theoretically shown that the dominant impairment due to turbulence in FSO-based QKD links is the beam spread, and the theoretical bounds for turbulent channels are derived.

In a practical implementation of a QKD scheme, there are the options of using DV- or CV- QKD, depending on the spectrum of the magnitude used to implement the quantum behaviour. The latter has the potential to approach the ultimate rate limits of quantum communication. In **[C3.16]**, a general framework was proposed for investigating the composable finite-size security of CV-QKD with Gaussian-modulated coherent-state protocols for a range of trust levels and the practical key rate for both optical fibre and optical wireless communications (i.e., VLC) networks. In **[C3.17]**, the experimental demonstration of CV-QKD was conducted over an optical fibre channel with various ranges of distance between Alice and Bob. DV-QKD using photons as the qubits relies on the generation of individual photons, or the use of decoy states to be able to take advantage of the properties of the quantum behaviour of photons. The polarization states of the photons can be established at the Tx and are measured at the Rx in a prepare and send scheme. Alternatively, a pair of polarization-entangled photons can be transmitted at the same time to both communicating agents.

Concluding remarks. VLC has the potential to provide increased data rates in the sixth generation and beyond wireless communication networks. However, the broadcast nature of wireless transmission and the superposition property allows eavesdroppers to attack the link and collect and amend the transmitted data before reforwarding it to the end-users. QKD is seen as a promising solution to improve transmission security by significantly employing quantum computing. The application of QKD in VLC systems can be expected in several areas (i.e., including banking systems, drone communications, vehicular communications, military, commercial, and personal area networks) however several research challenges must be addressed.

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Cluster 4: Digital, Industry and Space

Progress in digital and industrial technologies, including space, shape all sectors of the economy and society. They transform the way industry develops, produces new products and services, and are central to any sustainable future. As Europe gears up for a more resilient, green, and digital recovery, the EU needs to maintain a strong industrial and technological presence in key parts of digital, industrial, and other supply chains, in industrial ecosystems while safeguarding its ability to access to and use of space. This is critical not only to be able to compete globally, but also to protect citizens, deliver services and products of the highest quality, and preserve its values and socio-economic model.

In this context, four areas have been identified in which OWC would have a key role within the activities of this cluster, namely:

- Optical satellite communications for remote access
- Optical wireless intra satellite communication
- Future solutions for indoor optical wireless communications
- Optical wireless communications for industrial applications.

4.1 Optical satellite communications for remote access

Status. The space industry is growing enormously with variety of activities such as satellite launches, space exploration, telecommunications etc. According to the United Nations Office for Outer Space Affairs, there are more than 10,000s of satellites in orbit. One of the most common applications of those satellites in orbit is Earth observation. The main objective of such missions is to downlink huge amounts of observation data to the ground **[C4.1].** This is the main bottleneck for conventional RF communications. Free Space Optical (FSO) wireless communications can overcome this bottleneck. FSO communications have recently become very popular due to their ability to transmit data at very high data rates over longer distances, while consuming less power. In 2018, researchers at the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR) - in collaboration with ADVA - set at new record of 13.16 terabits per second for data transmission using free space laser communications. At this data rate, the content of all the printed books in the world could be transmitted in about 30 seconds. The ultimate goal of this mission is to provide broadband internet via satellite to rural areas, that are not connected to terrestrial network infrastructure **[C4.2].**

The application of FSO is not limited to the classical data communications but recently much interest and research has been focused on the satellite-based QKD, which pushes the boundaries of ground-based QKD systems that require very long fibre connections. This enables secure communications over very long distances, reaching areas where ground-based infrastructure is lacking. In 2018, China launched the first QKD satellite called “Micius”. It is world's first integrated quantum communications network, combining over 700 optical fibres on the ground with two ground-to-satellite links to achieve quantum key distribution over a total distance of 4,600 km for users across the country **[C4.3]**. Europe also plans to launch their first space based QKD system (Eagle-1) in 2024 in partnership with the European Space Agency (ESA), the European Commission and some European space companies **[C4.4]**. The project will provide evaluation mission data for the development and deployment of the European Quantum Communication Infrastructure (EuroQCI) **[C4.5]**. ESA plans to launch the Quantum Key Distribution Satellite (QKDSat) together with the UK company Arqit and a consortium **[C4.6]**.

Free Space Optical Communication covers a wide variety of scenarios ranging from LEO, MEO, GEO to ground for high data rate downlinks from satellites, inter-satellite links to enable relay scenarios etc. ESA’s HydRON is one of the great examples of such an application FSO scenario with a vision for an end-to-end optical high throughput optical space network **[C4.7]**. In addition, application scenarios such as air-to- ground, air-to-air links, high altitude platform (HAP) to ground or HAP to aircraft, etc. are also popular.

Current and future challenges. As mentioned above, FSO communication has many advantages and is currently the way to go for the long-range high throughput communication links. However, the main challenge is the atmospheric effect, which distorts the amplitude and phase of the signal and therefore reduces the BER of the system. In addition, environmental effects such as fog, clouds etc. can even completely block the signal. Some of the challenges identified for FSO communications are briefly explained below:

<u>Free space loss:</u> For all FSO scenarios, the signal travels through the atmosphere. The path is longer for lower elevation angles and shorter for higher elevation angles. The atmosphere attenuates the signal according to the distance between the two terminals. This loss is called free space loss.

<u>Absorption and scattering:</u> In addition to the general free space loss, there are various gas molecules and aerosol particles in the atmosphere that cause loss due to absorption and scattering effects. The effect is described by Beer’s law **[C4.8]**. Such atmospheric losses depend on the path, distance, wavelength and location of the ground terminal. If the ground station is located at a higher altitude in a clear environment, such effects are negligible. Therefore, the location of the ground station is usually chosen according to the availability of the link, but also at a higher altitude and in a clear environment whenever possible.

<u>Atmospheric turbulence:</u> Atmospheric turbulence: Due to variations in temperature and pressure in the atmosphere, it creates many turbulent cells called eddies of different sizes and different refractive indices. This causes constructive and destructive interference to the signal as it propagates through the atmosphere, causing beam wander and ultimately signal loss or degradation.

<u>Point ahead angle:</u> This is the angle by which the calculated pointing angle to the partner terminal differs from reality due to the relative motion between the transmitting and receiving terminals. This offset angle should be calculated and compensated for in advance to avoid the pointing loss. This effect is particularly significant in an inter-satellite link scenario where both terminals are moving relative to each other **[C4.9]**.

Advances in science and technology to meet challenges. The atmospheric channel degrades the quality of the signal which in turn deteriorates the BER performance of the FSO system. In order to improve the reliability of the system and avoid major losses, several mitigation techniques have been investigated and demonstrated. Some of them are briefly described below **[C4.9]**:

<u>Aperture averaging:</u> One of the simpler (however might be expensive) ways to mitigate the effect of atmospheric turbulence is to use a larger aperture. By Increasing the surface area of the receivers, relatively fast fluctuations caused by small-scale eddies are averaged out, reducing the fading channel.

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The parameter used to quantify this effect is called the aperture averaging factor, A_f . It is defined as the ratio of the variance of the signal fluctuations from a receiver with aperture diameter D to that from a receiver with infinite small aperture ($D = 0$) and can be expressed as:

$$A_f = \frac{\sigma_I{}^2(D)}{\sigma_I{}^2(0)}. \quad (4.1)$$

Diversity: The diversity technique also helps to mitigate the effects of atmospheric turbulence in the atmosphere and can be applied in time, frequency, or space. Space diversity is one of the more common approaches where more than one receiver or transmitter is used. If multiple copies of the same signal, which are mutually uncorrelated with each other, are transmitted to the receiver(s), the BER performance of the system will be improved. This can be achieved by transmitting the same signal at different times or frequencies so that they are mutually uncorrelated with each other.

Adaptive optics: Atmospheric turbulence also affects the phase of the laser beam. Aperture averaging only reduces the amplitude fluctuations. However, an adaptive optics technique mitigates the phase effect and delivers an undistorted beam through the atmosphere by pre-correcting it.

Automatic Repeat Request (ARQ): ARQ is widely used retransmission protocol used in data communications for reliability. In this protocol, the receiver always sends an acknowledgement when it receives data in the form of packets of a certain size is received. If the acknowledgement is not received within a certain specified time, the packets are retransmitted until a positive acknowledgement is received. This allows data to be transmitted more reliably.

Concluding remarks. In conclusion, FSO is attracting a great deal of interest from research institutes, academia, and industry because of its obvious advantage of long-range high bandwidth communications. In addition, satellite QKD has enabled greater application of FSO towards secure communications. However, there are several challenges such as the need for very accurate tracking, signal loss and distortion of signal due to atmospheric effects etc. With the advancement in the science and technology researchers and engineers have been able to investigate and demonstrate several mitigation techniques such as adaptive optics, various diversity schemes, adaptive modulation and coding to meet these challenges.

4.2 Optical wireless intra satellite communication

Status. While the development of terrestrial infrastructures for wireless network access such as 5G and now 6G has captured much of the research effort in recent years, other telecommunication solutions have also been developed and are in the pipeline. For example, many projects to provide global satellite communications services using tens of thousands of nanosatellites in non-geostationary orbits have recently been launched, among which the famous Starlink project. In this context, OWC is not only seen as a serious solution for earth-to-satellite and inter-satellite communications – as a complement to RF technologies which could rapidly become congested **[C4.10]** but is also being studied as a replacement for cables ensuring intra-satellite communications.

On the one hand, the replacement of communication cables by OWC links could enable non-negligible gains in mass, while the harness of a satellite represents up to 8% of its mass. This would allow more satellites to be carried on each launcher at a constant payload. On the other hand, the use of OWC links could greatly reduce the assembly and validation phase during the satellite manufacturing process, as these steps can currently take up to several months due to the complexity of the harness. In both cases, using OWC could thus help reducing dramatically the cost of deploying satellite constellations **[C4.11, C4.12]**.

Current and future challenges. The use of OWC links for intra-satellite communication is a very recent research and development topic, which faces many challenges. Firstly, the usual intra-satellite communication protocols were developed for wireline links and are therefore not necessarily suitable for OWC links. In particular, the multiplexing techniques they use are defined for links that are not very prone to interference. Conversely, the deployment of OWC links in a confined environment such as the interior of a satellite will necessarily lead to multiple reflections which may be detrimental to the reliability of communications. Another major challenge concerns the spatialization of OWC equipment, particularly transceivers. The electronic and optoelectronic components currently in use were designed for terrestrial applications that are much less constraining in terms of temperature, vibration, and radiation. It is therefore necessary to harden the proposed OWC solutions to make them compatible with space constraints.

Advances in science and technology to meet challenges. To meet these challenges, considerable efforts have been recently made by both academic and industrial actors. In **[C4.11]**, researchers from the Scuola Superiore Sant'Anna associated with engineers from Thales Alenia Space and supported by the European Space Agency (ESA) have proposed OWC transceivers compatible with the MIL-STD-1553B protocol, which is widely used for intra-satellite communications. This protocol uses on-off keying modulation and time division multiplexing to distribute data within several nodes at a rate of 1 Mbps and has constraints that OWC components can largely satisfy. At the same time, this group has demonstrated how reflections can be turned into an advantage to reach nodes in different compartments of a satellite, thus reducing its internal complexity **[C4.12]**.

In parallel, the company Oledcomm, associated with multiple partners among which the French National Centre for Space Studies (CNES) and the University of Versailles Saint-Quentin, has worked on the spatialization of the OWC technology. Transceivers compatible with the MIL-STD-1553B standard have also been developed and then optimized to meet market constraints while providing sufficient redundancy to ensure communication reliability. These efforts culminated in the launch, on 11 April 2023, of nano-satellites developed under the aegis of the University of Versailles Saint-Quentin and incorporating an OWC intra-satellite communication solution **[C4.13]**.

Concluding remarks. Although the performance of OWC links for intra-satellite communication has yet to be confirmed in a real space environment, the first tests carried out are very promising and suggest the potential of this technology for reducing the mass and production time of satellites, at a time when increasingly large constellations are to be deployed. Given the ability of OWC links to support very high data rates for multiple users, it is quite reasonable to assume that beyond these initial milestones, research and development will move towards the development of faster and more flexible solutions in terms of numbers of nodes, which may eventually lead to future dedicated standards.

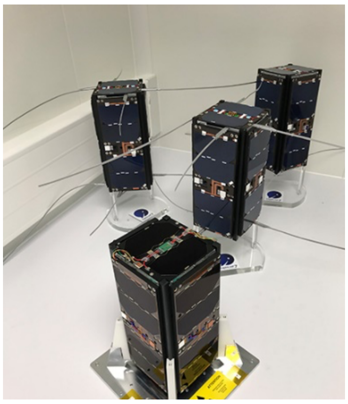

Fig. 4.1: *INSPIRE-SAT 7 nano-satellites, which integrate an OWC intra-satellite communication solution.*

4.3 Future solutions for indoor optical wireless communications

Status. Since the first works in the 1970s, OWCs for indoor network access – later called LiFi – have been the subject of numerous studies that have considerably pushed the limits of this technology in terms of throughput, range, latency but also compactness and energy and spectral efficiency. Data rates of several tens or hundreds of Gbps have been demonstrated, bringing the capacity of the OWC channel within an indoor room beyond Tbps **[C4.14-16].** From an industrial and commercial point of view, LiFi technology has also reached an advanced level of maturity. Several commercial product lines have recently emerged and are being deployed in a growing number of companies and organizations. LiFi, and more generally OWCs, therefore offer a wide range of advantages over radio, millimeter wave and terahertz communications that make it a particularly promising technology for 6G and future generations of WiFi, as evidenced by recent standardization efforts led within the IEEE and ITU **[C4.17]**.

Current and future challenges. However, the mass deployment of OWCs is currently limited by several obstacles. First, OWCs must be able to offer similar functions and performance to radio technologies in order to efficiently complement them. In the context of 6G, integrated sensing and communication (ISAC), i.e., simultaneous data transmission and localization between nodes, has been identified as critical.

At the same time, the range of OWCs is currently limited to a few meters indoors. This limitation comes from several factors. On the one hand, the optical power that can be emitted is constrained by various regulations, for lighting in the case of visible light sources and for photobiological safety in the case of infrared sources. These sources are also generally diffuse, which limits even more the power of the signal effectively emitted in the direction of the receiver. Finally, the photoreceptors traditionally used – PIN and avalanche photodiode – have a relatively limited sensitivity.

Another major obstacle to the mass deployment of OWCs is the compactness of their optical transceivers, which are still too bulky to be easily integrated into a wide range of user equipment, especially the smallest ones like smartphones. Miniaturization efforts are therefore necessary.

Advances in science and technology to meet challenges. To meet these challenges, many proposals have been made in recent years by academic and industrial actors. If research on ISAC is particularly active in the radio world, it is no less active in OWCs, where many works propose to integrate the achievements of the visible light positioning domain to light communications, with centimetric positioning resolutions and high data rates of several tens of Mbps [C4.18]. While high positioning resolution is fundamental for the implementation of the so-called location-based services that are so critical for 6G, it is also very useful to improve the performance of OWCs. Knowing where a terminal is located allows to know in which direction to direct its dedicated optical beam, using beamsteering solutions which can greatly improve the throughput and security of the communication link **[C4.16]**, as well as its range **[C4.19].** Other solutions have been proposed to improve this last metric, such as the use of extremely sensitive single photon avalanche diode (SPAD)-type receivers **[C4.20]**, which despite their limited bandwidth, can nevertheless ensure throughputs greater than Gbps**.**

SPAD receivers are also characterized by their very small sensitive area, which ensures a much better compactness than PIN or avalanche photodiodes and could thus make them serious candidates for the miniaturization of OWC transceivers. Many efforts have already been made on this subject, both on the academic side but also on the industrial side, notably by the companies pureLiFi and Oledcomm. Fig. 4.2 shows on the left the discrete transceivers used in the current LiFi product lines of these companies, and on the right the future generations of ASIC light antennas that they propose. Although much more compact, these antennas are however still constrained by the sensitive surface of their photodiodes, which will therefore greatly benefit from being reduced using SPAD.

Fig. 4.2: *Current commercial OWC transceivers (left) and their evolution toward miniaturized light antennas (right).*

Concluding remarks. Although OWCs have already made significant progress in recent years, their performance, particularly in terms of throughput, range, positioning resolution and compactness, can still be greatly improved. Several solutions are being worked on, including ISAC, beam steering and the use of SPAD photoreceptors, to achieve systems that are both compatible with the requirements of 6G and future generations of WiFi, and with industrial constraints of integration into user terminals.

4.4 Optical wireless for industrial applications

Status. OWC is useful where existing wireless technology reaches its limits. For instance, Wi-Fi is widely used in industry so that people ask for new spectrum which may be provided by OWC. Due to its short range, fundamentally limited by the walls, OWC can reuse spectrum more frequently than existing wireless systems. In very small cells, one or only a few users attach to one cell, thus reducing congestion a lot. Moreover, OWC is robust against electromagnetic interference and jamming from outside the building. For all these reasons, OWC provides service quality similar to a cable what makes it interesting for industrial applications **[C4.21]**. Following industrial use cases are under discussion: In the uplink, OWC can offload huge amounts of real-time sensor data from cameras, ultrasonic devices, LIDARS and RADARS (i.e., eyes of a mobile robot/automated guided vehicle, AGV) to the artificial intelligence in the cloud. In the downlink, this application requires more control type of traffic. Low latency is a major concern here. For wireless control, the link should be very robust, as transmission errors put mission-critical signals at risk, e.g., for emergency stop and remote driving **[C4.22].** In addition, OWC can be used in augmented reality for remotely assisted maintenance, i.e., deliver instructions and context information from remote experts to unskilled workers repairing a machine at a distant customer premise, e.g., by using a HoloLens **[C4.23]**.

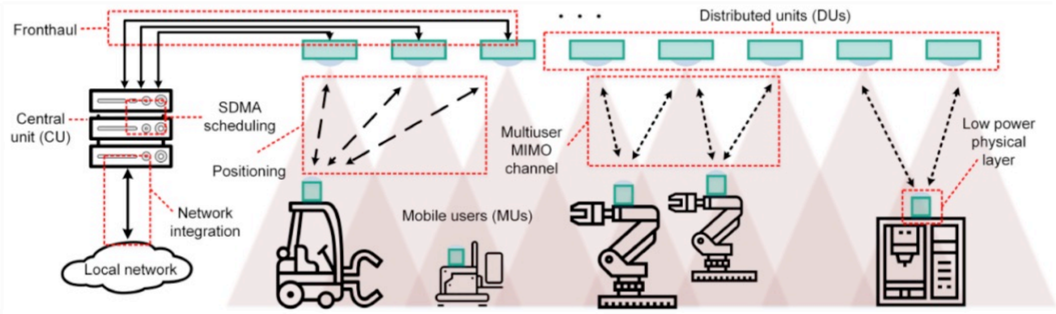

Fig. 4.3: *The distributed MIMO system is proposed for OWC in industrial applications. A first specification is contained in IEEE Std 802.15.13-2023, which also defines a low-power PHY, relaying and deterministic scheduler suitable for TSN.*

Current and future challenges The general challenge for industrial applications is to provide wire-like quality of service, i.e., reliability, low latency/jitter and high security, over wireless links while retaining mobility. For this purpose, some technologies have already been proposed and tested. These include distributed multi-user MIMO to provide sufficient network capacity and seamless mobility inside a wireless hotspot where OWC is available (Fig. 4.3). This architecture is implemented by serving signals of multiple mobile units jointly by using distributed optical frontends, denoted as remote units, connected to a central unit. Deterministic scheduling in space and time, coordinated by the CU, can deliver high data rate, low latency and zero jitter **[C4.24]**. A new pulsed-modulation physical layer enables sufficient data rates with lower power. Compared to the conventional OFDM PHY, with the same power, more overlap of cells can be realized. A MU is served by multiple DUs, so that a blocked LOS is no longer a risk for high reliability **[C4.25]**. These features have been added to the recent IEEE Std 802.15.13-2023, which is a specific standard for OWC in industrial applications **[C4.26]**. As future challenges, industrial applications could lower the cost and enable flexible deployment **[C4.27]**. While new full-coverage installations might probably use fibers, the deployment of hot spots may be more flexible by integrating OWC with power-line communications (PLC) as fronthaul between CU and RU **[C4.28]**. Precise positioning integrated with wireless communications is possible down to centimeter precision using LED transmitters and time-of-flight measurements **[C4.29]**, **[C4.30]**. 5G/6G integration is an ongoing research topic. While higher-layer integration of OWC using Multipath TCP **[C4.31]** and non-3GPP interworking function **[C4.32]** have been addressed, there are packet loss and latency during handover from OWC to RF. Integration at the PHY layer, i.e., reusing the RF waveforms unchanged over light as specified IEEE P802.11bb amendment to Wi-Fi 6 **[C4.33]** and MIMO with one antenna for RF and the other over light, is easily possible but has major drawbacks of i) using a sub-optimal waveform over the optical medium and ii) making channel access dependable on congestion in the RF medium **[C4.34]**.

Advances in science and technology to meet challenges. From the industrial communication perspective, the ideal interface for integration of RF and OWC may be above PHY plus lower MAC and below higher MAC, similar to multilink operation (MLO) currently defined in Wi-Fi 7, see also **[C4.34]**. A similar approach is dual connectivity in 5G. This would allow waveform and medium access to be optimized for OWC, besides no packet loss and zero latency during horizontal handovers to RF. While this interface is applied for 2.4, 5 and 6 GHz operations in Wi-Fi 7, industry refuses to open it for OWC. A current effort is to implement these ideas, demonstrate feasibility with reasonable effort **[C4.35]** and make the new features available for low cost by extending existing protocols in new chipsets **[C4.36]**. There is a big need to translate highly quoted scientific results on OWC in the open literature into agreed-upon specifications implemented by industry. These efforts should be more supported by future research projects. Different qualifications and a dedicated learning process are needed, therefore, as well as industry collaboration. Another research topic is quantum-computer proof security over industrial OWC links. It is expected that OWC is in principle more secure compared to RF-based wireless technologies, but this claim is based on intuitive arguments and not strictly proven yet. QKD is useful over fiber and sophisticated free-space optical links. But QKD requires single photons to be detected. OWC typically needs a much larger number of photons for robust transmission. The use of SPADs is possible and maybe helpful in other contexts. But with SPADs, the impact of ambient and sun light in real scenarios must be excluded. Alternatively, one could consider post-quantum cryptography, same as 6G research projects.

Concluding remarks. While OWC still aims to get into the mass-market, such as in residential areas, some of its niche applications, like industrial manufacturing, do have particular needs where light can leverage its unique features and, thus, complement RF by having no other option. Considering this as a challenge, may open a real market opportunity with moderate volumes in a scenario where higher infrastructure and device costs are acceptable. On the downside, industrial applications are among the most demanding ones and require features like ultra-high reliability and low latency/jitter, next to a high level of security, which are hard to realize in practice. OWC research into this direction finds support at the national and European levels. Solutions maybe demonstrable in 2025-26, and specifications in existing standards like IEEE Std 802.15.13 and ITU-T G.9991 are increasingly mature and can be used as a blueprint for future systems introduced together with, or even as an integral part of, 6G and Wi-Fi 8 in the 2030-time horizon.

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Cluster 5: Climate, energy and mobility

The United Nations has set a vison for global effort towards sustainable development goals (SDGs) in a decade of ambitious actions to deliver the Goals (including climate action, SDG13) by 2030. Likewise, this cluster, introduced by EU, aims to change the trend of climate change by looking into opportunities to make energy and transport sector more environmentally friendly, more resilient, smarter, and safer. Studies show that 1.5 to 4% of the greenhouse gas emissions are associated with the information and communication technology (ICT) sector **[C5.1]**, and by 2030, the ICT sector would demand energy amounts comparable to transport, industry, and residential sector **[C5.2].**

In this context, two areas have been identified in which Optical Wireless Communication (OWC) would have a key role within the activities of this cluster, namely:

- Energy efficiency of optical wireless communication systems
- Intelligent transportation systems using optical wireless technology

5.1 Energy efficiency of optical wireless communication systems

Status. As a communication technology that uses light to transmit data wirelessly, the OWC has several potential applications in the areas of climate, energy, and mobility, such as smart transportation systems, Internet-of-Things (IoT) devices, and smart buildings. The OWC technology has proven to be energy efficient, which is especially important for reducing power consumption while maintaining high data rates. In recent years, research has focused on further improving the energy efficiency of OWC systems through the use of advanced control systems, low-power components, and optimized system design (e.g., simultaneous data detection and energy harvesting using solar cells). Some of the key factors that affect the energy efficiency of OWC include the efficiency of the light source, the sensitivity of the photodetector receiver, and the use of energy-efficient modulation and encoding schemes.

Current and future challenges. There are several research issues and challenges in improving the energy efficiency of OWC systems. Some of the key challenges include:

1. Design of energy-efficient components: The efficiency of the light source, photodetector receiver, and other components in an OWC system can significantly impact its overall energy efficiency.
2. Optimization of the OWC system design: Optimization algorithms should be developed to balance the system parameters to maximize energy efficiency while maintaining performance metrics, such as data rate and latency.
3. Mitigating atmospheric effects: Atmospheric conditions such as fog, rain, and snow can significantly degrade the OWC system performance outdoors, resulting in increased power consumption to mitigate these effects and hence reduced energy efficiency.
4. Standards and regulations: There is a need for standards and regulations to ensure interoperability, safety, and energy efficiency of OWC systems. Joint work of research and industry is necessary to develop these standards and regulations, which can enable the widespread deployment of energy-efficient OWC systems.

Advances in science and technology to meet challenges. To address the challenge of designing energy-efficient components for OWC systems, development of new materials, new device structures, and fabrication techniques are required. For example, some recent studies have focused on the development of high-efficiency light sources (e.g., micro-LEDs, OLEDs, quantum dots, etc.), or on the use of new materials and structures for photodetectors (e.g., organic photodiodes) that can offer high sensitivity and low power consumption **[C5.3-5].**

To address the challenge of optimizing the OWC system design, the optimization algorithms should be developed in order to optimize the system parameters (e.g., transmitter and receiver parameters, etc.) to maximize energy efficiency while maintaining all communication requirements **[C5.6,7]**. Furthermore, OWC systems integration with different technologies is among the most common methods to achieve maximized energy efficiency. For example, reflective intelligent surface (RIS) based OWC systems have been proved as an appropriate method by using light reflections to design energy efficient VLC system **[C5.8]**; light based energy harvesting (based on solar panels or photodiode) is a promising solution for capturing and converting energy to obtain power supply from the received light signal to electricity **[C5.6-7]**; smart VLC enables joint communications and illuminations while maintain minimal energy consumption **[C5.9]**. In addition, addressing the trade-off between energy efficiency and data rate in OWC systems requires a holistic approach that considers the system design, modulation and coding schemes, and signal processing techniques, which requires interdisciplinary research between communication theory, optics, signal processing, and system design **[C5.10]**.

To achieve a decent OWC system performance, many mitigations techniques have to be upgraded to include the energy consumption criterion, such as adaptive optics, error control coding, adaptive modulations, and aperture averaging **[C5.10].** Finally, joint work of academy, industry and policymakers is required to establish standards and regulations for interoperability, safety, and energy

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efficiency of OWC systems. This can involve developing standards that encourage the adoption of OWC systems in different sectors, such as transportation, energy, and telecommunications, and provide funding for research and development of energy efficient OWC technologies.

Concluding remarks. Addressing these challenges will require multidisciplinary research efforts, involving research and industry experts in communication and information theory, optics, signal processing, materials science, computer science, and standardization. Overall, OWC is an area of active R&D, with ongoing efforts to improve its energy efficiency and performance, as well as to expand its range of applications as it has the potential to significantly reduce the energy consumption of wireless communication systems. As an energy-efficient, green and low-cost technology, the OWC represents a promising solution for variety applications in domain of climate, energy, and mobility.

5.2 Intelligent transportation systems using optical wireless technology

Status. A well-functioning transport system is the primary objective for achieving the concept of Intelligent Transportation Systems (ITS). ITS is today a sophisticated and still evolving paradigm, with the aim of forming an efficient and safe environment, regulating the people and goods movement. This paradigm encompasses the technological aspect, physical infrastructure as well as social aspects. Nevertheless, this paradigm requires investigation to reduce the carbon footprint of transportation. ITSs are built upon cooperation, connectivity, and automation of vehicles, and require highly reliable, robust and scalable vehicle-to-everything (V2X) communication solutions enabling vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) connectivity. Research efforts and standardization activities on V2X have been so far centered 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, 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 being. However, in the near future, high interference levels can be experienced in limited RF bands particularly in high-density traffic scenarios resulting in longer delays and packet rate degradation. To address such issues, visible light communications (VLC) has been proposed as an alternative vehicular access solution to RF-based V2X communications **[C5.11]**. Since automotive manufacturers are increasingly using LED-based exterior lighting, front and back vehicle lights can serve as wireless transmitters making VLC a natural vehicular connectivity solution.

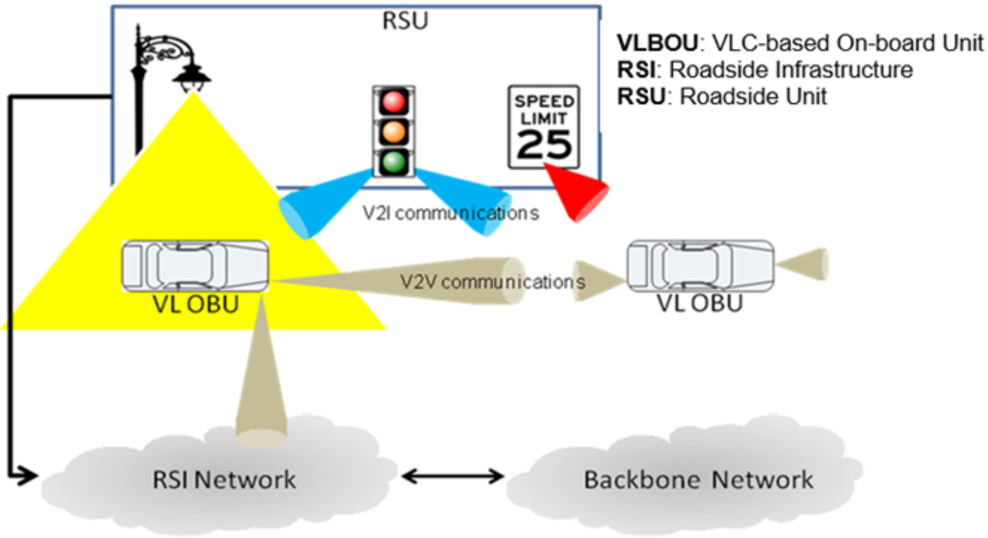

Fig. 5.1: *Illustration of a sample vehicular communication network using optical wireless technology.*

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Current and future challenges. In comparison to RF counterparts, VLC offers inherent advantages such as the 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 and high data speeds required in so-called infotainment applications. With such attractive features and application areas, vehicular VLC has received an increasing attention lately, see the surveys in **[C5.12]** and **[C5.13]** for a comprehensive description of the state-of-the-art in the field.

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 physical layers such as optical orthogonal frequency division multiplexing (O-OFDM) and its variants. O-OFDM was shown to be effective in handling the inter-symbol interference resulting from multipath propagation and limited bandwidth of LED. Multi-hop transmission techniques made possible the signal transmitted from the source vehicle to reach the destination vehicle through a number of intermediate vehicles (relays) eliminating the need of LOS requirements.

Hybrid VLC/RF links are further proposed to ensure link availability at all weather conditions. The superiority of solutions based on hybrid approaches in the context of ITS, is the core of **[C5.14].** In particular, the authors propose Li-Wi to better handle the handover mechanisms and validate their claim by means of experimental results. Even though the combination of different technologies is increasing momentum in the research and industrial community of ITS, several open issues still exist and need to be accounted for to make real and concrete advances in this sector. An important factor, limiting the use of hybrid wireless communication for ITS, is the lack of sufficient and deep experimental evaluation in real-world scenarios. This implies that several important factors that could hinder communication effectiveness, are not accounted for in current solutions. Just as an example, it has been shown the generation of the signals using electronic components, may introduce some interference in low frequencies **[C5.15].**

Advances in science and technology to meet challenges. The dynamic conditions imposed by the outdoor medium (i.e., adverse weather, effect of sunlight, etc.) and vehicle mobility necessitate the design of adaptive transmission solutions. At the physical layer, link adaptation might involve the selection of modulation type/size, channel code rate and/or transmit power based on the instantaneous received signal-to-noise ratio. On the hardware level, the vehicular VLC system can be modified to enable dynamic adaptation of its receiver 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 upper layers are further required. For example, most of medium access control (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 heterogenous 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.

Concluding remarks. With its low latency and high-rate transmission capacity, VLC has the potential to fulfill the requirements of both safety functionalities and infotainment applications. Experimental works have already demonstrated the feasibility of the vehicular VLC. Further research efforts are still required to address the dynamic conditions imposed by the outdoor medium and vehicle mobility before commercialization and a widespread adoption of this promising technology.

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Cluster 6: Food, bioeconomy, natural resources, agriculture, and environment

Climate change and human activities are creating a notable pressure on ecosystems and natural resources. Without fast and systemic transformative changes in the linear systems of production and consumption, the demand for natural resources will lead to serious negative effects for the planet. The circular economy, the sustainable bioeconomy, including its bio-based innovative circular ecosystems and solutions, sustainable agriculture, sustainable food systems, nature-based solutions, integrated water, soil, and nutrients management, as well as digitalisation and data technologies have the potential to balance environmental, social, and economic goals and set the economy on a course toward a sustainable development. Research generating new knowledge, a diversity of innovations, thriving place-based innovation ecosystems, industrial ecosystems, societal engagement and innovative business and governance models should be instrumental to unlock their potential.

In this context, four use cases have been identified in which OWC would have a key role within the activities of this cluster, namely:

- OWC for environmental monitoring
- Optical wireless sensor-based connectivity in oceans
- Optical wireless communications for sustainable smart agriculture
- Multispectral optical camera communications in smart farming.

6.1 OWC for environmental monitoring

Status. Visible Light Communications (VLC) can provide both high data rate and low-latency links whilst meeting green energy constraints. Thanks to its ability to illuminate and communicate at the same time, as well as its relatively low cost, it could be widely used in those scenarios where sensor nodes continuously need to exchange a large amount of data. The sensors may be of different kinds (e.g., temperature, humidity, video cameras, etc.) and can help to approach a world with a proper awareness of natural resources through technology. VLC can be considered as "green" technology, which can be optimized for remote control scenarios, since it is easy and cost-effective to build a smart network.

Traditionally, the use of VLC has raised with the aim of providing high data rate connectivity in indoor environments, as an alternative existing RF-based technologies such as Wi-Fi. Recently, VLC has emerged in the context of smart-agriculture and environmental monitoring. In such scenarios, not only sensor nodes can collect and send data through high data rate optical wireless links for remote control **[C6.1]**, but also illumination can vary to precisely match the growth needs of plants.

Current and future challenges. A particular scenario where VLC is expected as a candidate technology for environmental monitoring is the underwater one. The Internet of Underwater Things (IoUT) paradigm is defined as a worldwide network of heterogeneous interconnected underwater objects that communicate to each other for monitoring tasks of vast unexplored water areas **[C6.2]**. There are several real-time underwater applications such as marine ecology, pollution and water-based disaster preventions, seabed monitoring for scientific exploration to commercial exploitation.

The use of optical signals in the visible light range can provide high-speed underwater connectivity at lower latencies **[C6.3]**, as compared to acoustic and RF technology. Specifically, optical wireless communication has potential to reach a data rate that is higher than that of RF **[C6.4]**. Unlike RF signal which suffers severe absorption in sea water, the optical signal can achieve a relatively longer range in the order of tens of meters **[C6.5]**. All these advantages allow the use of optical waves for many real-time communication and control applications, such as large-scale IoUT and video-surveillance via both Autonomous Unmanned Vehicles (AUV) and divers, paving the way to practical solutions for more advanced underwater applications. However, VLC can suffer from high path loss due to water turbidity, which results in a medium range connectivity.

Advances in science and technology to meet challenges. An interesting underwater application relies on the use of VLC LoS links for water monitoring. Since the propagation of the optical signal is affected by water turbidity, such that parts of the incident signal is reflected and/or absorted generating a strong path loss, we can estimate the water turbidity level directly from the channel state information. Then, in case of perfect knowledge of the underwater environment, it will be possible to set accordingly the VLC links for link performance optimization. However, in case of natural conditions, where water type can change due to current variations and marine pollution, link performance in the form of, e.g., BER, can suffer of high and fast variations. In this regard, VLC performance can be then exploited for water monitoring (i.e., level of turbidity) that, as compared to COTS turbidimeters, is calibration-free tool that enables a faster implementation.

Finally, still in the context of environmental monitoring in indoor scenarios, VLC has been exploited order to monitor Particulate Matter (PM) concentrations, which in high concentrations are strictly correlated with severe pathologies **[C6.6]**. Specifically, it is designed a distributed network of PM sensors, each of them equipped with a couple of LED and Photodetector (PD) to exchange data information, to have a global but precise measure of concentration levels of PM. The main result is the possibility to avoid a prolonged exposure of fragile categories such as elders, children, or critical patients in wide indoor areas like hospitals, gymnasiums, and universities.

Concluding Remarks. The use of VLC technology for environmental monitoring is expected to achieve important outcomes, thanks to its green characteristics that allow the coexistence of optical signals in different contexts. The environmental monitoring represents an application of VLC sensing that coexists in addition to communication, illumination, and positioning via visible light. In the specific case of underwater monitoring, a VLC system can also be used as a water transparency monitoring system. To exploit this additional function, the underwater VLC system will not require any preliminary and additionally time-consuming calibrations in the field, unlike the measuring instrumentation that is currently available on the market.

6.2 Optical wireless sensor-based connectivity in oceans

Status. The world's oceans are a vast and complex ecosystem that provide valuable natural resources and environmental benefits. They play a critical role in regulating the Earth's climate, notably by absorbing carbon dioxide and heat from the atmosphere, as well as distributing heat around the planet, influencing hence weather patterns and the global climate. Ocean's currents, waves, and tides are also potential sources for generating renewable energies **[C6.7]**.

Unfortunately, oceans are facing significant threats from ever-increasing human activities that could result in pollution, overfishing, habitat and biodiversity destruction, and climate change. This calls for appropriate measures to protect the ocean, including actions involving ocean monitoring. One possible solution is using underwater wireless sensor networks to develop reliable statistical and mathematical models for changes in the water and air (weather) conditions, to drive effective and sustainable responses. Optical wireless communication is an interesting connectivity solution for such networks due to its higher energy efficiency and lower impact on the marine life, in comparison with acoustic communications, for instance. Such networks will enable efficient and (ideally) real-time sensing and monitoring of the underwater environment, which will allow taking appropriate measures for ensuring food security, preserving biodiversity, and offshore infrastructure surveillance **[C6.8, C6.9]**. Depending on the specific application, acoustic communication can be used as a complementary technology, e.g., when dealing with very large transmission distances.

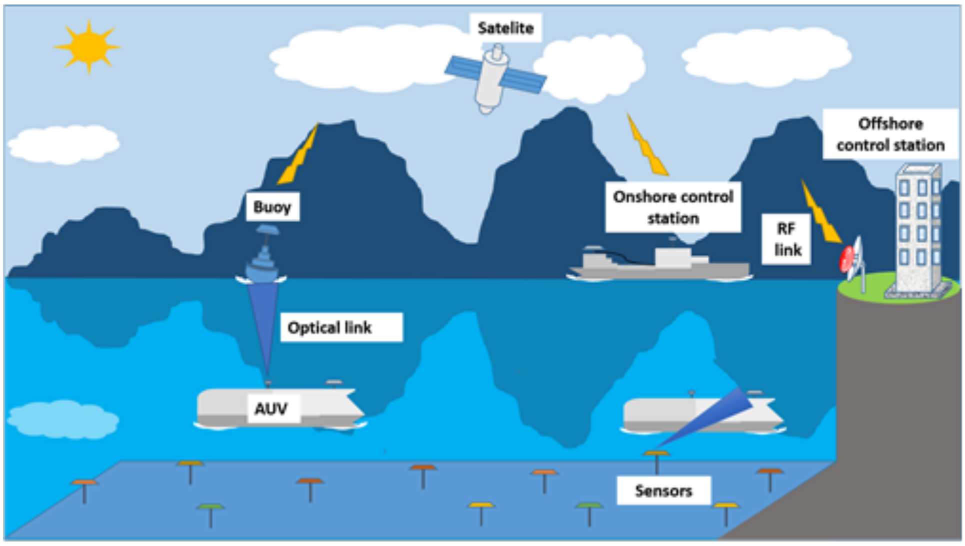

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***Fig. 6.1:** Illustration of an underwater sensor network used for oceanic monitoring.*

Current and future challenges. *"Data muling"* from underwater sensors is in fact a challenging task, where the difficulty depends on the required data rate, depth, and water quality, to mention a few of these challenges. The typical scenario is to deploy an underwater or surface drone, which establishes an optical link with the sensor (see Fig. 6.1). Then, link misalignments and low-precision localization will become other impairments affecting link reliability. The link range will be also affected by water turbidity, due to beam scattering and absorption mechanisms, as well as by oceanic turbulence, and probably beam blockage due to the presence of fish swarms. Also, depending on the operation depth, background radiation, coming from sunlight or underwater vehicle spotlights, can affect the transmission quality **[C6.9, C6.10, C6.11]**. Lastly, the battery lifetime of underwater sensors imposes constraints on the transmit optical power, which in turn, limits the transmission range and data rate.

Advances in science and technology to meet challenges. To address the previously listed challenges, several techniques and technologies need to be developed. To improve the link reliability, efficient signal transmission techniques should be designed to allow operation under challenging operational conditions, e.g., high water turbidity, long link distance, poor pointing accuracy, and high background noise level conditions. To extend the range, multi-hop transmission could be an option. When concerned with oceanic turbulence and beam blocking, diversity techniques and adaptive optics are among the most efficient.

To mitigate link misalignment, multiple transceiver configurations and emitting sources equipped with Micro-Electromechanical Systems-based or optical beam steering should be developed to alleviate insufficient pointing accuracy under exigent operational conditions **[C6.9, C6.10, C6.11]**. To reduce the energy consumption of underwater nodes, suitable routing protocols should be designed to minimize the amount of data that needs to be transmitted and to push the nodes to sleep mode except in case of sensing and data transmission. Also, depending on the application, energy harvesting technologies can be integrated into the underwater nodes to increase their battery lifetime. The use of ultra-sensitive photodetectors is another solution to enable working with low signal intensities.

Concluding remarks. Although the use of underwater optical communications in ocean monitoring applications is promising, there still exist many challenges for ensuring reliable data transmission under practical operational conditions. Among these challenges, the most important include dealing with link misalignments and pointing errors, extending the range of the current technology, working under high background noise levels, and guaranteeing low energy consumption and the use of low signal intensities to minimize the impact on marine life. Addressing these requirements will enable the wide-spread deployment of underwater observatories for the aims of ocean monitoring.

6.3 Optical wireless communications for sustainable smart agriculture

Status. Visible light communications were initially proposed for moving part of the wireless communications from the overwhelmed RF spectrum to the unregulated optical domain. Due to its characteristics, VLC can also be considered as an enabling technology for providing connectivity in some industrial applications or remote areas such as underground environments, warehouses, or hazardous atmospheres such as in oil/gas plants **[C6.12]**. Moreover, the use of Artificial Intelligence (AI), comprising Machine Learning (ML) or Deep Learning (DL), has been proposed during the last years for improving the efficiency of the industrial processes. In this context, the following question arises: *How can VLC improve the agriculture and food production?*

For indoor environments, such as granaries, farmsteads, cowshed, etc., achieving connectivity is typically subject to deploy a communication system on purpose (e.g., satellite or terrestrial cellular links), which simply provide a backhaul connectivity to access points. However, applications such as IoT services, positioning and resource monitoring or edge computing cannot be easily implementing in such large-sized cells deployments **[C6.13]**. Implementing VLC networks in these environments allows us to distribute the connectivity in multiple VLC access points. That is, the services could be implemented exploiting the satellite or cellular access point as a backhaul link. Moreover, indoor agriculture and food production indoor scenarios typically consider metallic roofs and other metallic elements, which hampers to achieve accurate positioning through satellite services. Consequently, autonomous vehicles or other machinery cannot be implemented because of the lack of accurate and reliable positioning and resources monitoring. VLC systems can potentially provide positioning services that solve this issue **[C6.14]**.

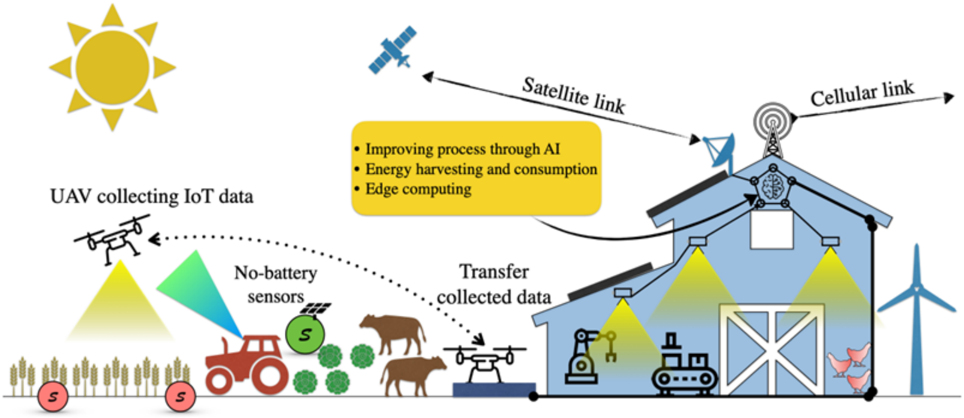

Fig. 6.2: *Smart farm involving light communications for both indoor and outdoor applications.*

Current and future challenges. It is worth recalling that providing IoT services and data processing requires capable and reliable connectivity, which is not available in most of the agriculture environments. In this sense, the use of Unmanned Aerial Vehicles (UAVs) equipped with a VLC system is proposed for collecting the IoT data from sensors (e.g., temperature, humidity, soil PH, etc.) deployed around the service area of interest **[C6.15]**. In this sense, vehicular VLC considering UAVs or other vehicles such as tractors or combine harvesters are currently issues to solve, which comprises aspects such as channel modelling, integration in the VLC systems or applications design. Furthermore, VLC allow us to implement no-battery sensors, which harvest the energy from small solar panels that charge a capacitor, transmitting the IoT data exclusively when it can be detected by the receiver. Once the information is "harvested", the data it returns to the agriculture/food production building to transfer the obtained data. At this point, the complete data set can feed AI algorithms for improving the food production chain. The set of data can be processes either in the agriculture/food production building or transmit the dataset through a dedicated backhaul link **[C6.16]**. Thus, it is necessary to design novel transmission schemes based on AI from the physical to networking layer to optimize, as final goal, the food production.

Advances in science and technology to meet challenges. VLC systems were initially proposed considering specific on-purpose LEDs for laboratory testbeds. In this sense, the evolution of the LED technology offers possibilities such as organic LEDs, µLEDs, or vertical-cavity surface-emitting lasers that may adapt to the requirements of the food production chain and agriculture environments. On the other hand, the development of autonomous vehicles has reached a technological mature, being possible and affordable to implement a VLC system in a vehicular system. On the other hand, simultaneous wireless information and power transfers has been very active in the last decades, specially, for RF systems. Therefore, the obtained knowledge can be useful for developing battery-less IoT systems. Finally, it is worth noticing that the first applications of AI into VLC systems are appearing in the State-of-the-Art. In this sense, they provide the first datasets that can potentially be the seed of the AI algorithms. Moreover, measurement campaigns are required to obtain accurate datasets for agriculture and food production.

Concluding remarks. In general, the introduction of VLC in the agriculture and food production chain enables the implementation of Industry 4.0 concepts such as autonomous vehicles, resource optimization through AI algorithms or, simply, allowing for remote management of the food production. Achieving these goals implicitly involves optimizing the energy consumption in line with the Sustainable Development Goals (SDGs) proposed by United Nations to be achieved by 2030.

6.4 Multispectral OCC for smart farming

Status. Farmers must be at the centre of any process of change in agriculture. Through appropriate technological tools and policies that ensure effective governance, farmers can be empowered to conserve biodiversity, protect ecosystems, and minimize environmental impacts. Smart farming **[C6.17]** consists of the use of new technologies that emerged at the dawn of the fourth Industrial revolution (Industry 4.0) in the field of agriculture and livestock to increase the quantity and quality of production, making the most of resources and minimizing environmental impact **[C6.18, C6.19]**.

With the advent of 5G and B5G mobile systems that promise high bandwidths, a new possibility for using cameras distributed in various locations are opened, which may act as access points for OCC-based sensor networks **[C6.20]**. This way, a new OCC Internet-of-Things (OCC-IoT) paradigm can be developed. For this, sensors with transmitting lights pointing at the cameras are needed, to dump the images into the cloud and decode the data.

Thus, taking advantage of the opportunities offered using OCC, a complete solution for smart farming could be proposed (see Fig. 6.3), using advanced analytics to process the collected data from the distributed optical cameras, facilitating the crop and livestock monitoring, animal identification, among other processes. Indicatively, UAVs equipped with cameras constitute an efficient way to collect heterogeneous data in a very short time, with reduced capital expenses.

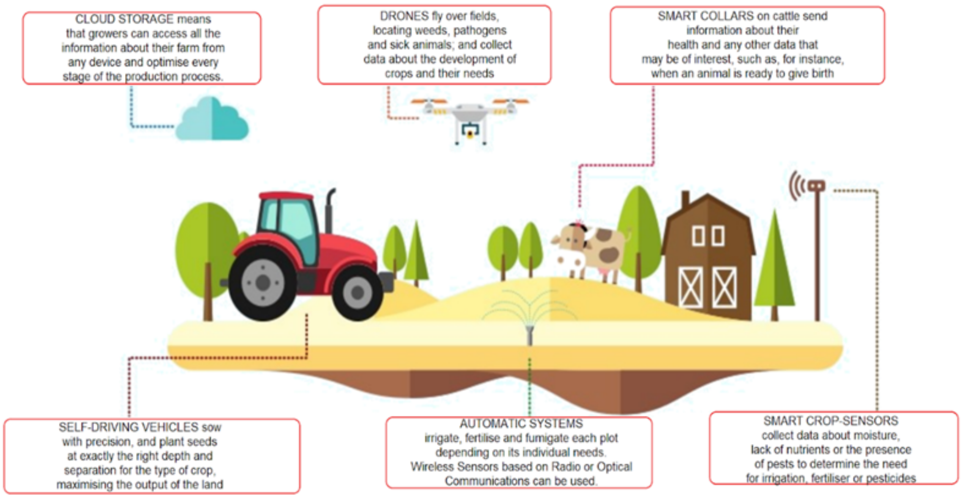

Fig. 6.3: *Description of the multispectral OCC technology applied in a smart farming scenario.*

Current and future challenges. Cameras are present in many devices and with OCC technologies, they become an optical receiver and provide communication capability to many devices (e.g., smartphones, tablets, laptops, etc.) detecting optical signals emitted by LEDs. In addition, they introduce some extra features such as a high receiving sensitivity that allows them to perform relatively long-distance links and introduce spatial-division multiple-access capability, allowing to distinguish between emissions coming from different sources in different locations.

For detecting a sensor transmission, the projection of the light data source on the image captured by a camera needs to be large enough. When we move away from the transmitter, and the projection of the source is very small, the projected image can become a single pixel. This may seem like a problem, but we can also turn it into an advantage. Even if it is only one pixel, or even less, the sensitivity of the camera allows us to detect the light energy at that point. This means that the camera can decode data from very distant or small emitters, but at the cost of a relatively low transmission rate (tens of bits per second at most, depending on the optical camera characteristics).

Advances in science and technology to meet challenges. Conventional Red-Green-Blue (RGB) cameras, such as those used in smartphones or surveillance systems, are the most widespread type of image sensors on the market. However, there are other types of images capturing devices that could provide communication capabilities. High spectral resolution devices, such as multispectral and hyperspectral cameras, introduce the ability to select a wider range of wavelengths. With them, it is possible to multiplex additional communication channels, apart from the typical RGB channels, for OCC links. OCC systems are based on conventional RGB cameras, which present several differences from multispectral cameras in capturing and generating images. So specific data detection and codification techniques must be developed and tested.

If a camera can discriminate the shift in spectral response of LEDs **[C6.21]**, these modifications can be contemplated as a new data channel. The main advantage is that new channels can be obtained from the same physical optical light source. Thus, the use of multispectral or hyperspectral cameras as OCC receivers is proposed to increase the number of available communication channels, taking advantage of the high spectral resolutions of the camera devices.

Concluding remarks. OCC technology can have a fundamental role in future smart farming applications, due to the ubiquity of the cameras embedded in most consumer electronic devices and their increasing capabilities, such as high resolution, faster scanning frequency, etc. However, high-spectral-resolution cameras, such as multispectral cameras, present characteristics that can be exploited to provide new features to OCC links. Furthermore, in these applications the multispectral camera is used as both a data receiver and remote image sensor to provide data for the calculation of the vegetation indexes, among others.

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