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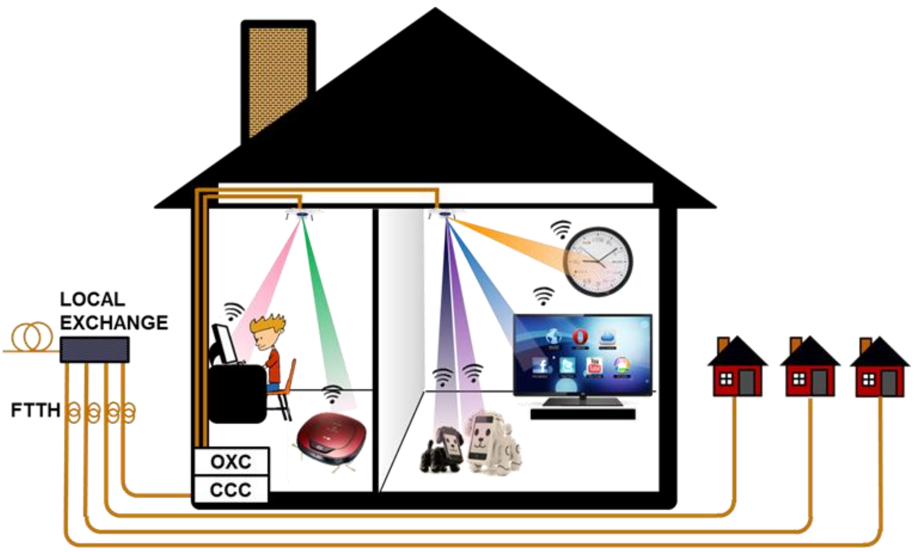
Optical Wireless Communication: options for extended spectrum use



REPORT

Report commissioned by the
Dutch Radio Communications Agency
(Agentschap Telecom)
Ministry of Economic Affairs and Climate policy

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Radiocommunications Agency
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Management summary

Optical Wireless Communication (OWC) may be an important alternative option that could ease the pressure on the radio spectrum that is now in use for communications. This report, commissioned by the Dutch Radiocommunications Agency gives an overview of current OWC technologies, trends and potentials. The Dutch Radiocommunications Agency aims to contribute these findings to ITU and CEPT. The report primarily focuses on broadband communication for indoor use.

There are several OWC technologies that offer a promising solution for indoor wireless broadband communication over a distance up to a few meters. Potentially OWC is suitable for very high bandwidth communication over these distances. OWC can exploit an enormous amount of yet unregulated spectrum (2600x the size of currently available radio spectrum) and can reuse this huge spectrum easily by spatial multiplexing, because the signal range is limited and in most cases confined to a room.

Two main OWC variants can be distinguished: Visible Light Communication and Beam Steered Infrared Light Communication.

Visible Light Communication (VLC) typically builds on the existing light-emitting diode (LED) ambient illumination system, and reuses the LEDs for data modulation. These LEDs typically have been designed for optimum illumination purposes, and have a limited modulation bandwidth. The VLC system thus covers a wide area, in which multiple user terminals have to share its capacity. The first generations of VLC products are already on the market, general referred to with the term 'Lifi'. These products use multiple (existing) LED lights for the downstream communication channel and infrared for the upstream communication channel. Current products facilitate up to around 50Mbit/s per access point. In theory the technology can facilitate multiple Gbit/s per access point.

Beam Steered – Infrared Light Communication (BS-ILC) brings the light only there where and when needed. Multiple beams may independently serve user terminals within the room, hence each terminal can get a guaranteed (non-shared) capacity without conflict with other terminals. Moreover, infrared light beams are allowed to be operated at higher power than visible light beams, as the eye safety threshold for infrared light is higher. Together with the directivity of a beam, this implies that the received signal-to-noise ratio with BS-ILC can be substantially higher than with VLC, enabling a higher data rate and longer reach at better power efficiency. Current BS-ILC prototypes facilitate multiple beams with over 10 Gbit/s per beam. Disadvantage is that this system is less usable for covering wider areas, and the required beam steering/tracking system makes it more complex than VLC. The BS-ILC variant is still largely in the laboratory phase, with different implementations including a hybrid radio-optical solution for the upstream communication channel.

Current and emerging OWC solutions can provide connections of medium to very high bandwidths (dependent on the solution) and very low latencies. They can therefore be used for a wide range of applications in environments where devices do not require a high degree of mobility and where the line-of-sight between sender and receiver is not blocked. OWC will never be a complete substitution for radio technologies, especially in situations where a line-of-sight is not always possible (e.g., to mobile devices carried inside clothing), or is likely to be blocked.

Principally, OWC can be used in a wide range of applications in a relatively static (non-mobile or nomadic) situation. It is potentially well-suited for high speed communication in applications such as HD video, augmented or virtual reality and fast downloads in environments with a high density of users, or where radio communication is not the preferred solution, like in offices, schools, stadiums, airplanes, hospitals, factory environments, chemical plants, etc., where it can potentially co-exist with existing and emerging radio technologies such as Wifi. It can also offer a wireless connectivity solution at places where radio communication is not allowed (e.g., in EMI-sensitive environments, such as intensive care rooms) or not feasible (e.g., in environments with heavy EM disturbances, such as near industrial welding robots). Whether and when OWC will become a commodity depends on several factors, such as the necessity (growth of data use), the growth of the capability of end user devices such as laptops, tablets and phones to process higher data rates, the availability of feasible alternatives (evolution of Wifi and 5G networks), the production costs, the establishment and evolution of OWC standards, and the interoperability features supported by the OWC solutions.

Also other elements in the communication 'value chain' between user and content may form potential bottlenecks that may influence the potential usability and uptake speed of OWC solutions: the evolution of speeds in access networks, the evolution of the in-building fixed backhaul which forms the communication link between the access network and the OWC indoor access points, and the evolution of OWC peripherals or components for end user devices.

Especially the indoor backhaul is an interesting link in the value chain. It is both a potential bottleneck as well as an area of opportunities, not only in the light of OWC development, but also when considering the trend towards smaller cells in radio networks in general. In businesses currently Ethernet cabling is used for data distribution. There is an emerging trend towards the use of Power over Ethernet for connecting both lighting and other low power equipment such as access points and sensors. This also relates to the trend towards more energy-efficient and more intelligent LED lighting solutions in buildings. In homes also Ethernet or Power over Ethernet can be used, or in some cases Powerline Communication (PLC) is a feasible option for lower data rates.

There is no regulation for the visible light and near-infrared light spectrum. This is different from the radio spectrum, where there are many and complicated regulations for radio spectrum, such as the RE and EMC Directives that limit radiation of equipment to reduce interference with other equipment and spectrum regulations allocating frequencies to different services. OWC is an emerging technology. Due to the characteristics of the used spectrum and the localised use of OWC applications regulations such as for other spectrum bands seem unnecessary. However standardisation of OWC protocols is necessary to increase interoperability. Some companies are starting to offer commercial products for VLC/Lifi. There is no major ongoing standardisation effort in this area yet, but IEEE has started to get interested in this field by having established an IEEE 802.15 Task Group 7R1 on OWC technologies in 2015. Supported by some manufacturers of 'Lifi' products for VLC, an effort has been started to reuse parts of the Wifi Suite (IEEE 802.11). An IEEE 802.11 Light Communications Study Group has been started as a first step towards standardisation of VLC as part of 802.11. Other options include reusing part of ITU-T G.hn, which could ease the interworking with in-building Power Line Communication (PLC) solutions.

Safety issues by OWC are of limited concern, as equipment needs only low power and does not emit radio waves. Therefore OWC may be an interesting communication solution for environments such as hospitals and airplanes. Also it may be appealing in situations where EM hypersensitivity is assumed. However, there are stringent safety considerations regarding the use of visible light or infrared radiation, which are for a large part already covered by regulations regarding light safety. The most critical human organ is the eye. The effect of visible light or infrared radiation on the human body depends on the wavelength, power density, and exposure time, but also some protection measures are needed with regard to epileptic sensitivities. In addition, OWC elements and also the necessary communication backhaul and power supply for OWC access points need to be safe to install, inspect and maintain.

One of the main trends in communication networks is the evolution from large cell sizes (macrocells) offering low to medium capacities/user data rates (Mbit/s) to small cell sizes (pico/femtocells) offering large capacities (Gbit/s). The increased capacity in conjunction with the reduced cell size yields a substantially increased capability to handle dense traffic needs. This trend opens possibilities for a technological ecosystem to compete and/or complement each other according to use cases. OWC can provide a very efficient way to offer wireless ultra-high bandwidth communication over short distances, without impact on radio spectrum. In principle, optical solutions may provide a more energy-efficient and therefore cheaper alternative for communication than a combination of electrical wired and radio wireless communication. However, the business case of OWC solutions highly depends on economies of scale and the application domain. E.g., OWC can now already be attractive for certain niche markets where radio spectrum is becoming scarce or the use of radio frequencies is complicated or discouraged. For the mass market, OWC product adoption is still in the 'innovators' phase, but OWC solutions become more and more interesting and are becoming available at lower costs.

Recommendations

1. Optical wireless has been evaluated in lab environments successfully. VLC/Lifi products start to be offered on the market or are already at high technology readiness level (TRL). We recommend to ***start one or more pilot projects where VLC/Lifi and BS-ILC are tested in practical situations***.

2. It is also recommended to ***stimulate close contacts between (national) industrial R&D and academic research***, as there is (still) much diversity in the OWC technologies being explored. Early identification of which are potential winning technologies among them and facilitating and promoting convergence and interworking will support the industrial development and speed up market introduction.

3. OWC is not replacing, but is complementing the use of other transmission as e.g. Wifi for in-building communication infrastructures in which OWC can off-load the bandwidth-hungry applications from Wifi. Due to this co-existence with the current Wifi technology, we recommend ***designing and building offices, public spaces and houses such that the potential of OWC is taken into account*** *especially for creating the fixed (wired) infrastructure accommodating sufficient OWC access points and backhaul****.*** Combining transporting data with powering optical wireless Access Points using Ethernet cables (Power over Ethernet) becomes increasingly interesting, and therefore it is recommended to pay attention to it for construction purposes.

4. For optical wireless, eye- and skin-safety are the most critical issues. Although the use of optical wireless by the general public can be made safe for almost all conditions, we recommend to ***take a closer look to safety issues for people who are working in a close proximity of intense light sources for installation and maintenance.***

5. There are still challenges to overcome before being deployed commercially. We recommend to ***focus more on standardisation efforts by ITU or IEEE rather than governmental rules and limit governmental regulation primarily to limits with regard to health***

hazards, carbon footprint, and commercial competition. Standardisation will increase not only compatibility among industrial products but also compatibility with already deployed technologies.

6. The deployment of Optical Wireless Communication may be particularly interesting in environments where many high bandwidth demanding users access the network within a confined space, or where conventional radio technologies cannot be used, or cannot provide the necessary service level. ***Bringing together representatives from potential user groups, construction industry, communication industry, device manufacturers and solution providers*** may help to further advance use cases and requirements for standards and further developments and to identify niche markets where the introduction of OWC will be most beneficial.

7. Acceptance and deployment of OWC will benefit from a clear vision on interworking with existing or emerging popular wireless standards, such as Wifi, for instance in the area of authentication, encryption and seamless roaming between Access Points. It is recommended to ***promote reuse of existing solutions where possible, for instance with regard to authentication and signal encryption.*** Such reuse may ease the development of interworking mechanisms (for instance handovers) between OWC and radio communication technologies. Also this way of new developments with a still relatively small user base may benefit from improvements of solutions with a large user base.

Dutch management summary

Optische draadloze communicatie, ofwel Optical Wireless Communication (OWC) kan een belangrijke alternatieve vorm van draadloze communicatie zijn die de druk op het radiospectrum kan helpen verlichten. Dit rapport, in opdracht van Agentschap Telecom, geeft een overzicht van de huidige OWC-technologieën, -trends en –mogelijkheden. Ook hoopt Agentschap Telecom dat de bevindingen uit dit rapport kunnen bijdragen aan het werk van ITU en de CEPT op het gebied van Optical Wireless Communication. Het rapport richt zich primair op breedbandcommunicatie voor gebruik binnenshuis.

Er zijn verschillende OWC technologieën die een veelbelovende oplossing kunnen bieden voor draadloze breedbandcommunicatie over een afstand van enkele meters. OWC is potentieel geschikt voor zeer hoge bandbreedte communicatie over deze afstanden. Het kan een enorme hoeveelheid van het nog niet gereguleerde spectrum gebruiken (2600x groter dan het huidige beschikbare radio spectrum) en het kan gemakkelijk dit enorme spectrum hergebruiken door spatial multiplexing, omdat het signaalbereik beperkt is en in de meeste gevallen beperkt tot een ruimte.

Er zijn twee OWC hoofdvarianten te onderscheiden: Visible Light Communication en Beam Steered Infrared Light Communication.

Visible Light Communication (VLC), draadloze communicatie door middel van zichtbaar licht, bouwt voort op het bestaande omgevingslichtsysteem (LED) en gebruikt de LED's opnieuw voor datamodulatie. Deze LED's zijn ontworpen voor optimale verlichtingsdoeleinden en hebben een beperkte modulatiebandbreedte. Het VLC systeem bedient op deze wijze vanuit een verlichtingsbron een (relatief) groot gebied, waarin meerdere gebruikersterminals hun capaciteit moeten delen. De eerste generaties VLC producten zijn al op de markt, meestal aangeduid met de term 'Lifi'. Deze producten maken gebruik van meerdere (bestaande) LED lampen voor het downstream communicatiekanaal en infrarood voor het upstream communicatiekanaal. Huidige producten kunnen tot circa 50Mbit/s per toegangspunt leveren. In theorie kan VLC per toegangspunt meerdere Gbit/s leveren.

Beam Steered – Infrared Light Communication (BS-ILC), draadloze communicatie door middel van gestuurde infraroodbundels, brengt het licht alleen daar waar en wanneer dat nodig is. Meerdere bundels kunnen onafhankelijk gebruikersterminals in de ruimte bedienen, zodat elke terminal een gegarandeerde (niet-gedeelde) capaciteit kan krijgen zonder conflict met andere terminals. Bovendien mogen infraroodlichtstralen met een hoger vermogen dan zichtbare lichtbundels worden gebruikt, omdat de oogveiligheidsdrempel voor infraroodlicht hoger is. Samen met de mogelijkheden die een gerichte infraroodbundel biedt betekent dit dat de ontvangen signaal-ruisverhouding met BS-ILC aanzienlijk hoger kan zijn dan bij VLC, waardoor een hogere gegevenssnelheid en een groter bereik bij een betere energie-efficiëntie mogelijk zijn. Huidige BS-ILC prototypes werken met meerdere bundels waarbij elke bundel meer dan 10 Gbit/s kan leveren. Het nadeel van dit systeem is dat het minder geschikt is voor het dekken van een groot gebied, en het vereiste beam steering/tracking system maakt het complexer dan VLC. De BS-ILC variant bevindt zicht nog grotendeels in de laboratoriumfase, met verschillende implementaties waaronder een hybride radio-optische oplossing voor het upstream communicatiekanaal.

Huidige en opkomende OWC oplossingen kunnen verbindingen bieden van gemiddelde tot zeer hoge bandbreedte (afhankelijk van de oplossing) en zeer lage vertraging ('latency'). Ze kunnen daarom worden gebruikt voor een breed scala aan toepassingen in omgevingen waar apparaten geen hoge mobiliteit vereisen en waarbij de zichtlijn tussen zender en ontvanger niet wordt geblokkeerd. OWC zal echter nooit een volledige vervanging zijn voor radiotechnologieën, vooral in situaties waarin een directe zichtlijn niet altijd mogelijk is of waarschijnlijk wordt geblokkeerd (bijv. voor mobiele apparaten in broekzak, jaszak of tas).

In principe kan OWC worden gebruikt voor een breed scala aan toepassingen in een relatief statische (niet mobiele of nomadische) situatie. Het is potentieel zeer geschikt voor hogesnelheidscommunicatie bij toepassingen zoals HD-video, augmented of virtual reality en snelle downloads in omgevingen met een hoge gebruikersdichtheid, of in situaties waar men radiocommunicatie wil beperken of ontlasten, zoals in kantoren, scholen of stadions, vliegtuigen, ziekenhuizen, fabrieksomgevingen, chemische fabrieken, enz., waar het potentieel naast bestaande en opkomende radiotechnologieën zoals Wifi kan bestaan. Het kan draadloze connectiviteit bieden op plaatsen waar radiocommunicatie niet is toegestaan (bijv. In EMI gevoelige omgevingen, zoals intensive care kamers) of niet haalbaar (bijvoorbeeld in omgevingen met zware EM-storingen, zoals dichtbij industriële lasrobots). Of en wanneer OWC een algemeen goed wordt, hangt af van verschillende factoren, zoals de noodzaak (groei van datagebruik), de groei van het vermogen van eindgebruikersapparaten zoals laptop, tablets, en telefoons om hogere datasnelheden te verwerken, beschikbaarheid van haalbare alternatieven (evolutie van Wifi- en 5G netwerken), de productiekosten, de vaststelling en evolutie van OWC normen en de interoperabiliteitsfuncties die worden ondersteund door de OWC oplossingen.

Ook andere elementen in de communicatie 'waardeketen', tussen gebruiker en inhoud, kunnen potentiële knelpunten vormen die de mogelijke bruikbaarheid en opnamesnelheid van OWC oplossingen kunnen beïnvloeden. Zoals de evolutie van snelheden in toegangsnetwerken, de evolutie van de 'indoor backhaul', de vaste communicatiestructuur in huizen of kantoren die de communicatieverbinding tussen het toegangsnetwerk en de OWC indoor toegangspunten vormt, en de evolutie van OWC randapparatuur of componenten voor eindgebruikersapparaten.

Vooral de 'indoor backhaul' is een interessante schakel in de waardeketen. Het is zowel een potentieel knelpunt als een gebied met kansen, niet alleen in de ontwikkeling van OWC, maar ook als we kijken naar de trend van kleinere cellen in radionetwerken. In bedrijven wordt momenteel Ethernet bekabeling toegepast voor gegevensdistributie. Er is een opkomende trend naar het gebruik van Power over Ethernet voor het verbinden van zowel verlichting als andere apparatuur met een laag vermogen, zoals toegangspunten en sensoren. Dit heeft ook te maken met de trend naar meer energie-efficiënte en intelligentere LED-verlichtingsoplossingen in gebouwen. In woningen kan ook Ethernet of Power over Ethernet worden gebruikt, of in sommige gevallen is Powerline Communication (PLC) een haalbare optie voor lagere gegevenssnelheden.

Er zijn geen specifieke wettelijke regelingen voor het zichtbare en nabije infrarood lichtspectrum. Dit is anders dan voor het radiospectrum, waar veel en gecompliceerde voorschriften gelden, zoals de RE- en EMC-richtlijnen, die de straling van apparatuur beperken om interferentie met andere apparaten te verminderen, en spectrumregelingen die frequenties toewijzen aan verschillende diensten. OWC is een opkomende technologie. Vanwege de kenmerken van het gebruikte spectrum en het lokale gebruik van OWC toepassingen lijken voorschriften met betrekking tot specifieke (zichtbaar licht of infrarood) spectrumbanden onnodig. Standaardisatie van OWC protocollen is echter noodzakelijk om de interoperabiliteit te vergroten. Sommige bedrijven zijn al begonnen met het aanbieden van commerciële producten voor VLC / Lifi. Er is op dit gebied nog geen belangrijke standaardisatie-inspanning. Wel is in de IEEE in 2015 de IEEE 802.15 Task Group 7R1 over OWC technologieën opgericht. Met steun van enkele aanbieders van 'Lifi' producten wordt voor VLC getracht om delen van de Wifi Suite (IEEE 802.11) opnieuw te gebruiken. Een IEEE 802.11 Light Communications Study Group is opgericht als een eerste stap in de richting van een VLC standaard als onderdeel van 802.11. Andere opties zijn hergebruik van een deel van ITU-T G.hn, wat de samenwerking met interne Power Line Communication (PLC) oplossingen zou kunnen vergemakkelijken.

Veiligheid is een beperkt aandachtspunt bij OWC, omdat apparatuur slechts een laag vermogen nodig heeft en geen radiogolven uitzendt. Juist daarom kan OWC een interessante communicatieoplossing zijn voor omgevingen zoals ziekenhuizen en vliegtuigen. Ook kan het aantrekkelijk zijn in situaties waar EM overgevoeligheid wordt verondersteld. Wel van belang zijn echter de strenge veiligheidsoverwegingen met betrekking tot het gebruik van zichtbaar licht of infraroodstraling, die voor een groot deel al zijn afgedekt door voorschriften met betrekking tot de lichtveiligheid. Het meest kritische menselijke orgaan is het oog. Het effect van zichtbaar licht of infraroodstraling op het menselijk lichaam hangt af van de golflengte, de vermogensdichtheid en de belichtingstijd, maar er zijn ook enkele beschermingsmaatregelen nodig met betrekking tot epileptische gevoeligheden. Bovendien moeten OWC elementen, maar ook de nodige communicatie-backhaul en voeding voor OWC-toegangspunten veilig zijn om te installeren, inspecteren en te onderhouden.

Een van de belangrijkste trends in communicatienetwerken is de evolutie van draadloze en mobiele netwerken met grote cellen (macrocellen) met lage tot middelgrote capaciteiten/gebruikersdatasnelheden (Mbit/s) naar draadloze communicatie door middel van steeds meer en kleinere cellen (pico/femtocells) met grote capaciteiten (Gbit/s). De verhoogde capaciteit in combinatie met de verminderde celgrootte levert een substantieel verhoogd vermogen op om met dichte verkeersbehoeften om te gaan. Deze trend opent mogelijkheden voor technologische ecosystemen om te concurreren en/of om elkaar aan te vullen, afhankelijk van de usecase. OWC kan een zeer efficiënte manier bieden om draadloze ultrahoge bandbreedtecommunicatie over korte afstanden aan te bieden, zonder impact op het radiospectrum. Optische oplossingen kunnen in principe een energie-efficiënter en dus goedkoper alternatief voor communicatie bieden dan een combinatie van elektrische bedrade en radio draadloze communicatie. De businesscase van OWC-oplossingen is echter in hoge mate afhankelijk van schaalvoordelen en het toepassingsdomein. OWC kan nu al aantrekkelijk zijn voor bepaalde nichemarkten waar het radiospectrum schaars wordt of het gebruik van radiofrequenties gecompliceerd of ontmoedigd is. Voor de massamarkt bevindt de adoptie van OWC zich nog in de fase van 'innovators', maar OWC-oplossingen worden steeds interessanter en komen beschikbaar tegen lagere kosten.

Aanbevelingen:

1. Optische draadloze communicatie is succesvol gedemonstreerd in lab omgevingen. VLC/Lifi producten worden al op de markt aangeboden of bevinden zich al op een hoog ‘Technology Readiness Level’ (TRL). We raden aan om **één of meer pilotprojecten te starten waarbij VLC / Lifi en BS-ILC in praktijksituaties kan worden getest.**

2. Het wordt ook aanbevolen **om nauwe contacten tussen (nationale) industriële R&D en academisch onderzoek te stimuleren**, omdat er (nog steeds) veel diversiteit in de OWC technologieën wordt onderzocht. Vroegtijdige signalering van potentieel winnende technologieën onder hen en het faciliteren en bevorderen van convergentie en interworking zullen de industriële ontwikkeling ondersteunen en de marktintroductie versnellen.

3. OWC vervangt niet, maar vormt een aanvulling op het gebruik van andere uitzendingen zoals: Wifi voor interne communicatie-infrastructuren waarin OWC de bandbreedte hongerige applicaties van Wifi kan ontladen. Vanwege de noodzakelijke co-existentie met de huidige Wifi technologieën, is het **aanbevolen om kantoren, openbare ruimtes en huizen zodanig te**

ontwerpen en te bouwen dat rekening wordt gehouden met de potentie van OWC, vooral voor het creëren van de vaste (bedrade) infrastructuur waarin voldoende OWC toegangspunten en backhaul zijn ondergebracht. Het combineren van datatransport en het leveren van stroom voor optische draadloze toegangspunten met behulp van Ethernet-kabels (Power over Ethernet) wordt steeds interessanter, en daarom wordt aanbevolen om er aandacht aan te schenken voor constructiedoeleinden.

4. Voor optisch draadloos zijn oog- en huidveiligheid de meest kritieke problemen. Hoewel het gebruik van optisch draadloos door het grote publiek veilig kan worden gemaakt voor bijna alle omstandigheden, **raden we aan om veiligheidskwesties nader te bekijken voor mensen die in de buurt van intense lichtbronnen werken voor installatie en onderhoud**.

5. Er zijn nog uitdagingen te overwinnen voordat er commercieel kan worden ingezet. We raden aan om meer te **focussen op normalisatie-inspanningen door ITU of IEEE in plaats van door overheidsregels en om overheidsregulering in de eerste plaats te beperken tot limieten met betrekking tot gevaren voor de gezondheid, koolstofvoetafdruk en commerciële concurrentie.** Standaardisatie verhoogt niet alleen de compatibiliteit tussen industriële producten, maar ook de compatibiliteit met al geïmplementeerde technologieën.

6. De inzet van optische draadloze communicatie kan vooral interessant zijn in omgevingen met hoge bandbreedte gebruikers binnen een beperkte ruimte die het netwerk nodig hebben, of waar conventionele radiotechnologieën niet kunnen worden gebruikt of niet het vereiste serviceniveau kunnen bieden. **Het samenbrengen van vertegenwoordigers van potentiële gebruikersgroepen, de bouwsector, de communicatie-industrie, apparaat fabrikanten en oplossingsleveranciers** kan helpen om verdergaande gebruikscasussen en -vereisten voor normen en verdere ontwikkelingen te bevorderen en nichemarkten te identificeren waar de introductie van OWC het meest voordelig zal zijn.

7. De acceptatie en inzet van OWC zal profiteren van een duidelijke visie op samenwerking met bestaande of opkomende populaire draadloze standaarden, zoals Wifi, bijvoorbeeld op het gebied van authenticatie, encryptie en naadloze roaming tussen toegangspunten. Het wordt aanbevolen **om hergebruik van bestaande oplossingen, waar mogelijk te bevorderen, bijvoorbeeld met betrekking tot authenticatie en signaalversleuteling**. Dergelijk hergebruik kan de ontwikkeling van interworking mechanismen (bijvoorbeeld handovers) tussen OWC en radiocommunicatietechnologieën vergemakkelijken. Ook deze manier van nieuwe ontwikkelingen met een nog relatief kleine gebruikersgroep kan baat hebben bij verbeteringen van oplossingen met een groot gebruikersbestand.

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1 Introduction

1.1 Background

The Radiocommunications Agency in the Netherlands is facing a fast growth of mobile data use, and foresees even more growth in the future: many trends such as Internet of Things, and Smart Grids ultimately lead to more and more spectrum use.

Visible (or near visible) Light Communication (VLC) might be an important alternative option that could ease the pressure on the radio spectrum that is now in use for communications.

The Dutch Radiocommunications Agency aims to make an inventory of the trends and analyse the potential and contribute the findings to ITU and CEPT as a new preliminary draft Report in response to ITU-R Question 238/1 (see Annex A), to be able to support a better international insight in solutions and alternatives for spectrum scarcity.

The questions in 238/1 are:

1 What are the distinctive characteristics and efficiency gains of the use of visible light for broadband communications in terms of their use of the spectrum?

2 What are the overall objectives and user needs for the development of broadband communication in the spectrum area of visible light?

3 What are the new applications associated with visible light used for broadband communications?

4 What are the technical and operational characteristics, taking into account considering [that optical broadband needs to avoid human hazards], needed for the further development of visible light communications?

1.2 Motive

Radio bandwidth is a scarce resource, especially in crowded areas

The exploding need for wireless communication capacity is getting beyond the capabilities of traditional radio techniques. The available radio bandwidth gets exhausted, wireless devices start interfering with each other in this overcrowded radio spectrum, and high-capacity radio is power-hungry. Optics can offer a breakthrough, by means of the huge bandwidth of its spectrum, together with intelligent networking. Also the very short range is both a possible limitation as well as an important feature, as it enables reuse of the same spectrum within relatively short distances.

The demand for high bandwidth communication keeps growing

In the past couple of decades, increasingly more devices are capable of connecting to a wireless network, ranging from a smartphone to indoor lighting control devices. Developments that have contributed to this are technological innovations and more affordable hardware. To effectively utilise these peripherals, numerous broadband applications have been developed such as a weather, social, financial, or media etc. applications. The bandwidth requirements for any of these applications varies but more importantly, they all need a stable and reliable connection for it to work properly (e.g. for potentially life-critical applications such as health monitoring). However, as stated above, these devices have to work in an overcrowded radio spectrum. In addition to the increasing numbers of devices and applications, people are using them for a longer period of time and also more intensively, with a growth in connection speed by 50% per year for high-end user's (see Figure 1). This is because of streaming applications like Netflix or Social media applications, which require constant updates and a high bandwidth. Furthermore, both trends combined lead to more users close to each other, especially in some environments such as offices, schools, conference centers, restaurants and hotels, shopping malls, stadiums, and public transportation.

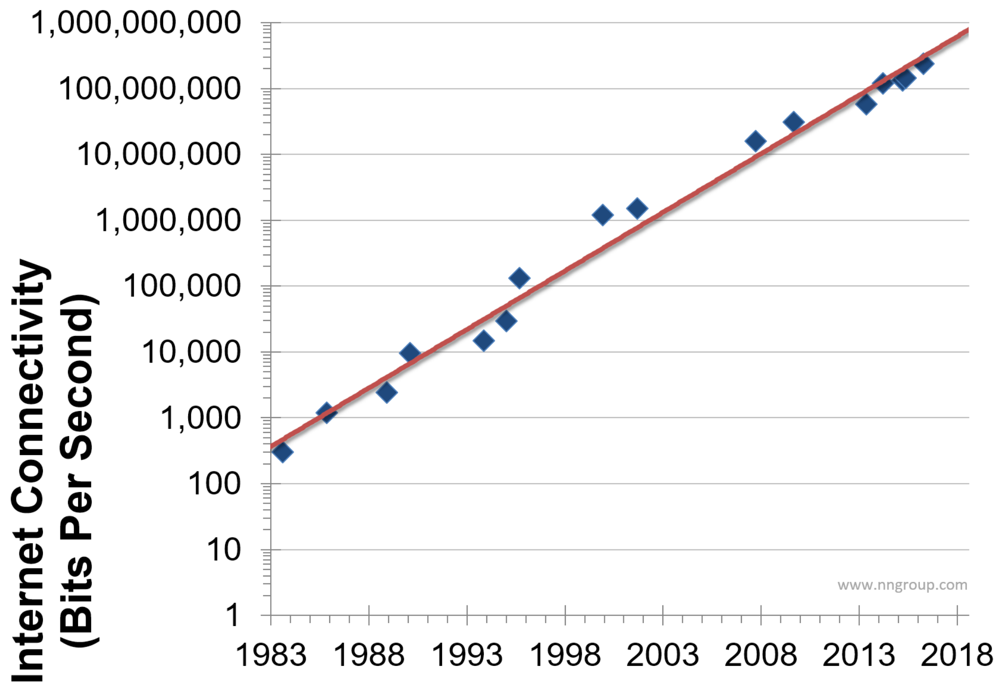


Figure 1: Nielsen's law on Internet Bandwidth: A high-end user's connection speed grows by 50% per year (source: https://www.nngroup.com/articles/law-of-bandwidth/)

The number and use of wireless devices grows

The use of wireless devices has become a commonplace at home, in (flexible) office environments and on the move, and for these instances most people use a smartphone, tablet or laptop computer to read emails, stream video, update their social media, e-shopping and buying of groceries. This shows how wireless devices have become integrated in our daily lives. This is especially true at home with the development of Smart Homes where each home electronic device (e.g., for controlling lighting, heating, household appliances) is connected wirelessly. The benefit of these devices being wirelessly connected is the freedom of control that it can provide in- and outdoors. For instance, a person can control his lighting or check his security when he is at home, in the office or on vacation. In addition wearable devices like smartwatches continuously provide information wirelessly in the vicinity of the wearer. All of these wireless devices can collect and provide information and some are capable of automatically processing the data through the Internet and deliver the results to the user. It is also possible for these devices to automatically decide which step to take based on the information collected. This interconnection between wireless devices and the use of the Internet is called, The Internet of Things (IoT) and has grown rapidly in the past decade with more than 50 billion connected devices expected in 2020, see Figure 2.

Communication via visible or infrared light offers a potential solution

The aforementioned trends have resulted in many wireless devices working closely together, because of this the radio spectrum becomes more and more crowded, which is causing interference. Communication via visible or infrared light is an attractive option to alleviate the burden on the radio spectrum. Currently research is being conducted on the possibilities of optical wireless communication and there are proof of concepts (e.g. beam steered infrared light communication) to prove the feasibility of the concept. Furthermore, early products are emerging based on optical wireless communication for office spaces.

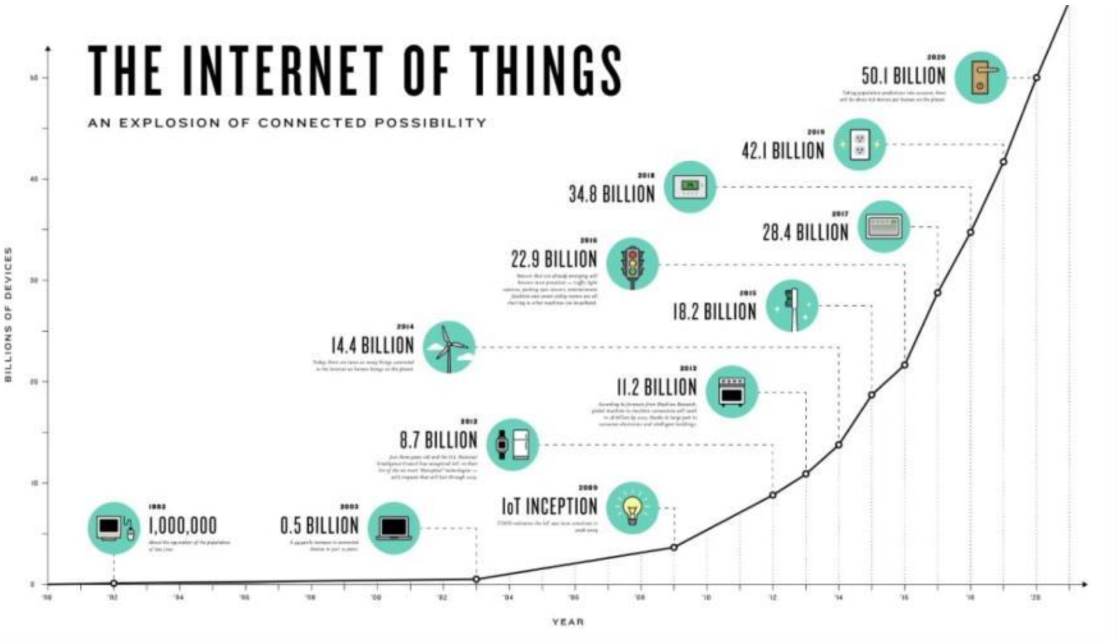


Figure 2: Growth of number of devices (source: Cisco/TheConnectivist/NCTA)

Main research question:

- With the increasing dependence on wireless devices and the imminent congestion of the crowded radio spectrum, optical wireless communication holds great potential to alleviate the radio spectrum. Therefore the main research question that needs to be answered is: *In what respect and in which way(s) can (near) visible light communication be used to relieve the use of radio spectrum?*

1.3 Scope

OWC can be applied in a variety of situations and on a number of ranges.

- **Ultra-short range OWC**: chip-to-chip communications in stacked and closely packed multi-chip packages.

- **Short range OWC**: wireless body area network (WBAN) and wireless personal area network (WPAN) applications under standard IEEE 802.15.7, underwater communications.
- **Medium range OWC**: indoor infrared (IR) and visible light communications for wireless local area networks (WLANs) and inter-vehicular and vehicle-to-infrastructure communications.
- **Long range OWC**: inter-building connections, also called Free-Space Optical Communications (FSO).
- **Ultra-long range OWC**: inter-satellite links.

This research primarily focuses on indoor broadband OWC applications, however an overview of OWC applications in other ranges is given in section 2.6.

1.4 Approach

The approach consisted of three major stages illustrated in Figure 3. The first stage consisted of desk research and interviews (see Annex B) as a means to collect information and data on the ecosystems, properties, value chain components, and to identify the stakeholders. This was followed by interviews with a number of selected parties, a stakeholders analysis, complimented by a workshop with several experts and stakeholders where an issue and potential analysis was performed (see Annex B), and some additional interviews. In the final stage reporting and presentation were drafted and reviewed.

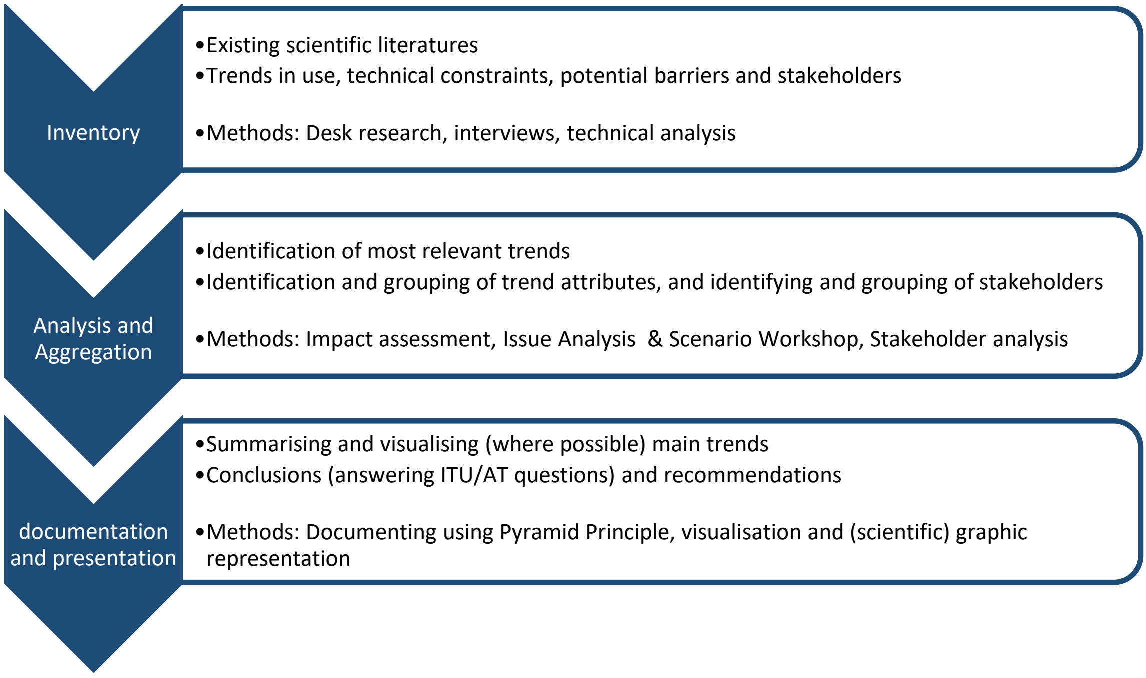


Figure 3: Overview of approach with three major stages

1.5 Overview

This report will describe four important aspects of optical wireless communication (OWC), consisting of the technical, deployment, business and regulatory, and main trends.

The report will first describe the technical aspects, in chapter 2, starting with the characteristics and spectrum use of OWC (e.g., EMI-insensitivity and the use of a license-free spectrum), followed by the application types and suitability of optical wireless communication. In addition it will also look into the security and safety aspects.

This is followed by the deployment aspects that are described in chapter 3, which also looks at the adaptability and connectivity of OWC to other telecom systems, and the adaptability and standardisation of building/construction.

The business and regulatory aspects, the barriers, accelerators and stakeholders for current and future OWC solutions and relevant standards organisations and developments are discussed in chapter 4. Chapter 5 investigates main trends that can have an impact on OWC development and deployment and also looks at first products and first users of OWC. Finally, in chapter 6 conclusions and recommendations are given.

2 OWC technical aspects and trends

This chapter describes the technical aspects of optical wireless communication technologies, focusing on applications for indoor medium range use. The first section briefly describes the application areas and rationale behind OWC developments. The second section describes the different OWC technology ecosystems for medium range indoor use and the developments and trends in these ecosystems. Subsequent sections describe safety, security and privacy aspects. The final section describes OWC applications in other ranges and environments.

2.1 Applications and application environments

In general, Optical Wireless Communication is especially fit for environments where radio is (or will be) less feasible because of a combination of:

- spectrum scarcity;
- need for very high capacity;
- reluctance to use radio technology;
- need to avoid electromagnetic interference;
- legislation;
- need for wireless transmission that can be contained within the building.

In these situations price is only a secondary factor in the technology choice. However when OWC becomes more mainstream and its application volume grows, bandwidth consumption grows further and prices of OWC equipment drop, OWC may also be a good solution for more general office and home applications. Its relative ease of installation and high privacy level makes it attractive for residential services at home and for business applications.

Application environments where OWC is particularly interesting

OWC is not hampered by electro-magnetic interference (EMI) nor does it generate interference for EM-sensitive devices, it is nearly impossible to jam and offers a high level of privacy (e.g., does not penetrate walls), its installation is relatively easy, and it provides a huge license-free spectrum. Building on its ability to selectively cover small areas, by means of spatial reuse it can offer a large aggregated capacity.

These characteristics are advantageous in densely-populated environments where people may have high traffic demands, such as in open office rooms, conference halls, exhibition halls, airplane cabins, train compartments, gaming halls, etc. Its EMI-insensitivity enables robust highly-reliable communication such as needed for industrial manufacturing robots, intra-data center top-of-the-rack interconnects, temporary (disaster-recovery) networks, etc. Atmospheric conditions may hamper its use for outdoors, in particular over longer reaches and in foggy conditions. Mobile backhauling for small radio cells (spaced several hundreds of meters), car-to-car and car-to-roadside communication are examples of attractive outdoor scenarios.

Future applications that may drive demand for OWC technologies

Many efforts have been done to predict specific applications for access technologies. But in reality what will be the most important applications and devices in more than a few years is very difficult to predict. Think about 'internet', 'smart phones', 'tablets' and 'navigation systems', the success of which is only predicted at the moment the success already started.

Success of applications is driven by worldwide success of combination of devices / operating systems / fixed and mobile infrastructures / existing application ecosystems.

In general some predictions can be made about data traffic:

- Peak data rates for applications will keep growing;
- Data traffic will become more symmetrical (upstream will become more important) but in general there will always be more downstream traffic than upstream to end users;
- Longer 'bursts' of traffic (more and more video);
- Low latency becomes more and more important.

In general some predictions can be made about devices (see also 1.2):

- More and more multi-purpose end user devices will be used in situations where now single purpose devices are used;
- The growth of Internet of Things components (sensors, actuators, etc) has just begun. Everything will be connected, always.

2.2 OWC Technology ecosystems in medium range indoor use

As illustrated in Figure 4 two major categories of indoor OWC techniques may be distinguished: visible light communication (VLC) and beam-steered infrared light communication (BS-ILC).

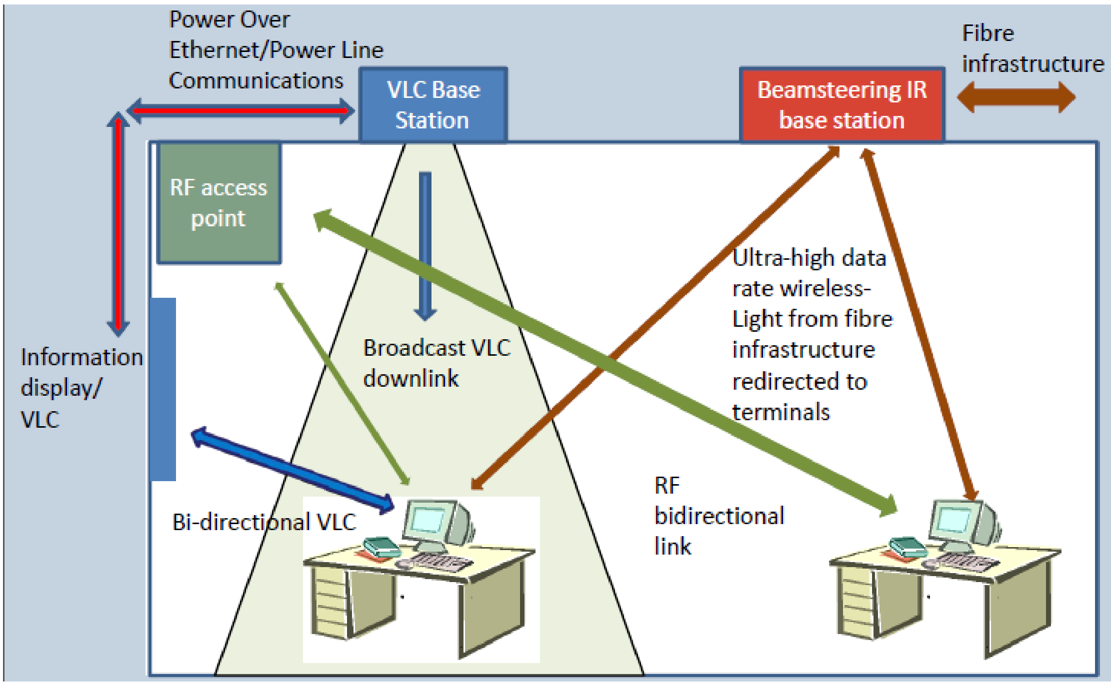


Figure 4: Basic indoor OWC options (from [1])

- ***Visible Light Communication (VLC)*** typically builds on the existing light-emitting diode (LED) ambient illumination system, and reuses the LEDs for data modulation. The VLC system thus covers a wide area, in which multiple user terminals have to share its capacity by a suitable MAC protocol. Moreover, the received light intensity decreases with the squared distance to the LED source, thus limiting the signal-to-noise ratio (SNR) and hence the reach. VLC requires that the illumination is switched on, which may not always be desired but for instance newer VLC variants are able to also communicate with lower light levels (e.g., when users prefer a dimmed-light setting when watching a movie on TV, …). The first generations of VLC products are already on the market (see also paragraph 5.2)
- ***Beam Steered – Infrared Light Communication (BS-ILC)*** brings the light only there where and when needed. Multiple beams may independently serve user terminals within the room, hence each terminal can get a guaranteed capacity without conflict with other terminals. The directivity of a beam implies that the received SNR can be substantially higher than with VLC, enabling a higher data rate and longer reach at better power efficiency. Moreover, IR light does not reach the vulnerable retina in the human eye, which implies that relatively high transmitted power levels are allowed within the eye safety limits (up to 10mW for λ>1.4μm, according to IEC 60825, ANSI Z136). Furthermore, photodiode responsivity basically is proportional to wavelength, and 1.5μm beam-steered systems can advantageously build on well-established fiber-optic system components. Disadvantage is that this system is less usable for covering wider areas, and the added beam steering system makes it more complex than VLC. This variant is in the laboratory phase.

Table 1 gives a brief overview of the two main OWC variants comparing the two variants with each other and with the IEEE 802.11 suite (Wifi).

Table 1: OWC variants compared with IEEE802.11 suite[1]

	VLC	**BS-ILC**	**Wifi IEEE 802.11**
Cap. per user	Shared; 8 Gbit/s over 1m	Unshared; very high (up to 112Gbit/s per beam)	Shared; 802.11n (2.4GHz): <600Mbit/s 802.11ac (5GHz): <6.93Gbit/s 802.11ad (60GHz): <7Gbit/s
Reach	Short-medium (few m) Needs LoS	Medium (<10m)-long Needs LoS	Medium Does not need LoS (<60GHz)
Energy consumption	High (Watts); illumination needs to be on	Low (per beam, <10mW), on-demand only	Base station >100mW
Carrier freq., av. bandwidth	400-700nm; width 320THz	1460-1625nm (S+C+L bands); width 20.9THz	2.4GHz band; width 83.5MHz channels 20 or 40MHz 5GHz band; width 575MHz channels 20 or 40 or 80MHz 60GHz band; width 7GHz
Safety aspects	Penetrates eye If collimated: <<1mW	Does not penetrate eye; collimated <10mW	EM hypersensitivity issues
Containment of signal to room (Privacy and reduced interference)	Moderate (visible light contained by walls, but may leak through windows)	Moderate to Good (IR light only in narrow beams and contained by walls, and leaks through windows are prevented in situations where windows have IR reflection coating)	Worse; in most situations the signal is not contained by walls.
Infrastructure	Share LED illumination	New indoor (fiber) infra	Electrical cable (Cat5) infra
Standardisation	First steps made IEEE 802.11 LC study group	Not yet	Extensive, mature, keeps evolving Backwards compatible
Utilisation	First products on market	Laboratory phase	Very wide spread; more Wifi devices than people on earth; >50% of internet traffic through Wifi

The two OWC variants are discussed in more detail in the 2.2.1 (VLC) and 2.2.2 (BS-ILC). This is followed by a description of characteristics of the OWC receiver for client devices in paragraph 2.2.3 and a discussion on hybrid optical/radio wireless networks in paragraph 2.2.4.

2.2.1 Visible Light Communication (VLC) techniques

LEDs which are primarily designed for illumination purposes typically deploy a blue LED chip plus a phosphor coating which converts this blue light into the white light (see Figure 5a). The slow decay time of the phosphor severely limits the bandwidth to a few MHz only. Some im-

[1] See also paragraph 2.4 for more detailed considerations with regard to safety and privacy

provement is obtained when filtering the blue LED light at the receiver, but the bandwidth is still restricted (typically <20MHz). Employing this blue-filtering and basic non-return-to-zero (NRZ)-On-Off Keying (OOK) modulation, 40Mbit/s transmission has been achieved at an illumination level of 700 lux (office areas require 200-800 lux) [2]. Spectrum-efficient advanced modulation schemes are to be used in order to realise higher data rates. By applying orthogonal frequency division multiplexing (OFDM) with 256 subcarriers and bit-loading, in conjunction with a pre-equalising filter before the LED driver and a blue filter before a photodetector followed by an amplifier, a net data rate of 2.0Gbit/s over 1.5m free-space reach was achieved, and 0.79Gbit/s over 3m [3].

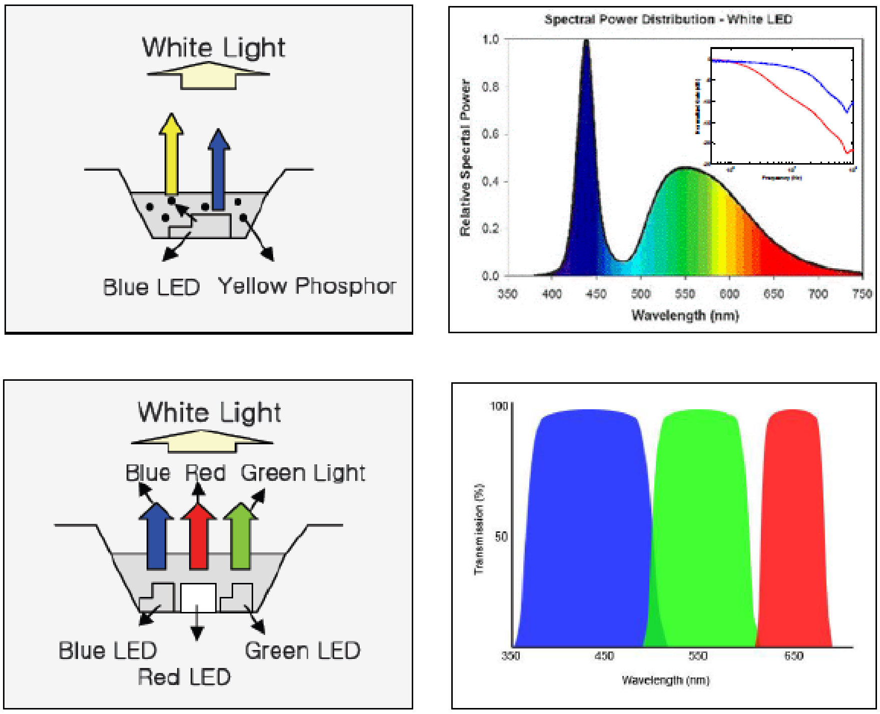


Figure 5: LED types for VLC; a) Blue LED + phosphor, b) RGB multi-element LED [4]

Alternatively, white light may be produced by a multi-element LED, composed of tri-color elements (red + green + blue; see Figure 5. Although, each of the LED elements may have a limited bandwidth (typically some 15MHz), by modulating them separately the capacity can be tripled. The wavelength division multiplexing approach requires a more complex driver at the transmitter-end, and three color-filtering stages in parallel at the receiver. Taking this approach, and using baseband OFDM a.k.a. discrete multi-tone (DMT) modulation with 512 subcarriers and color-filtering avalanche photodetector receivers, 3.4Gbit/s was achieved over 10cm (at 410 lux), and 2.2Gbit/s over 30cm (at 25 lux) [5]. With a quad-color LED (red + green + blue + yellow) and tailored carrierless amplitude phase (CAP) modulation (128-CAP for red, 32-CAP for green, 64-CAP for blue, 128-CAP for yellow), an aggregate capacity of over 8Gbit/s over 1m was achieved (see Figure 6) [6].

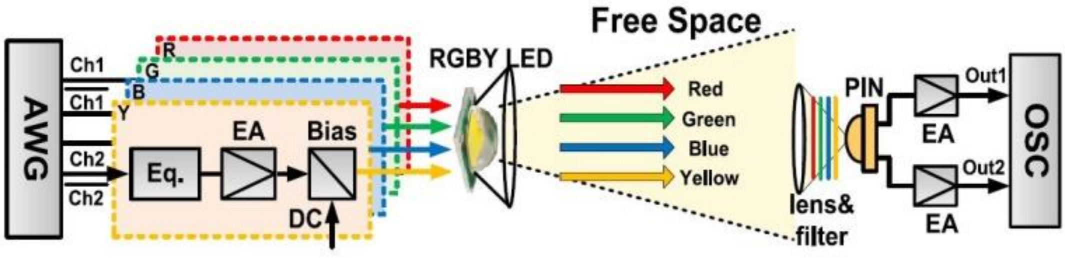


Figure 6: 8Gbit/s quad-color VLC system using CAP modulation [6]

The integration of lighting and communication functions brings particular challenges, as the consumer should not perceive any light flickering effects and dimming the light over a wide range should be possible, while communication should continue to be supported. Within IEEE 802.15.7, standards are set for high-speed VLC up to 96Mbit/s. Another route to increase VLC's capacity is spatial multiplexing. By deploying 9×9 MIMO[2] techniques based on a blue 450nm μLED array and 2D APD array, 7.48Gbit/s over 0.5m reach was achieved [7].

VLC systems dubbed Lifi are becoming available commercially, e.g. offering bidirectional 40Mbit/s optical wireless connectivity through a USB dongle at the user terminal [8]. Also directional VLC systems offering up to 1Gbit/s two-ways with <2ms latency are offered [9].

2.2.2 Beam-steered infrared light communication (BS-ILC) techniques

Dynamically adaptive 2-dimensional steering of multiple beams is needed to establish links to multiple (non-stationary) user terminals. The first concepts of beam-steered infrared light communication were introduced in 1999 [10].

Actively controlled devices such as micro-electro-mechanical system (MEMS) mirrors and spatial light modulators (SLMs) have been reported; these require a separate control channel. Per beam an active steering device is typically needed, which compromises scaling to many beams. Using an SLM operating in a spatially multiplexed way, multiple beams can be holographically steered [11]. Combined with an angle magnifier module, operation with 6 beams carrying 37.4Gbit/s each over 3m and a field-of-view (FoV) of 60 deg, has been reported [12]. With 2D MEMS-based mirrors, 7mW beams were steered over >20 deg and offered 10Gbit/s downstream [13].

Alternatively, the beam steering can be done with static diffractive devices, which do not need local powering nor a separate control channel (see Figure 7). The steering is controlled by changing the wavelength of the optical data signal fed to the device; thus this control is embedded in the data signal itself, which simplifies the network's architecture and the network control. The optical data signals are fed to the steering device by means of an indoor fiber network, from remotely located tuneable laser transmitters. These transmitters all may be located at a centralised site, which eases maintenance and upgrading. The system's architecture is exemplified in Figure 7. Laser tuning times are typically much shorter than the tuning times of a MEMS-based mirror or SLM, hence the beam steering can be much faster. Examples of this approach are 1D steering with a plane reflection grating [14], and transmission at 10Gbit/s OOK with steerable pencil beams over 2.5m [15]. Upscaling the system to steer multiple beams can be achieved by simply feeding multiple wavelengths to the diffractive device. By using a number of narrowband Bragg gratings in a photo-thermo-refractive glass volume, an equal number of

[2] multiple-input and multiple-output, radio techniques using sending and/or receiving equipment with multiple antenna's

beams can be supported [16]. 2D beam steering can be achieved with two cross-aligned diffractive gratings by interleaving of their respective small and large free spectral range (FSR) [17][18] (see Figure 7). This concept can also be realised with a virtually imaged phased array (VIPA) providing the small FSR [19]. Compact, but more lossy, photonic integrated circuits have been reported which provide 2D beam steering by wavelength-tuning plus local phase-tuning of an arrayed waveguide grating router (AWGR) [20][21]. Stepwise wavelength-tuned 2D beam steering may be achieved by a large port-count AWGR module with its output fibers put in a 2D array followed by wide aperture lens [22] (see Figure 7).

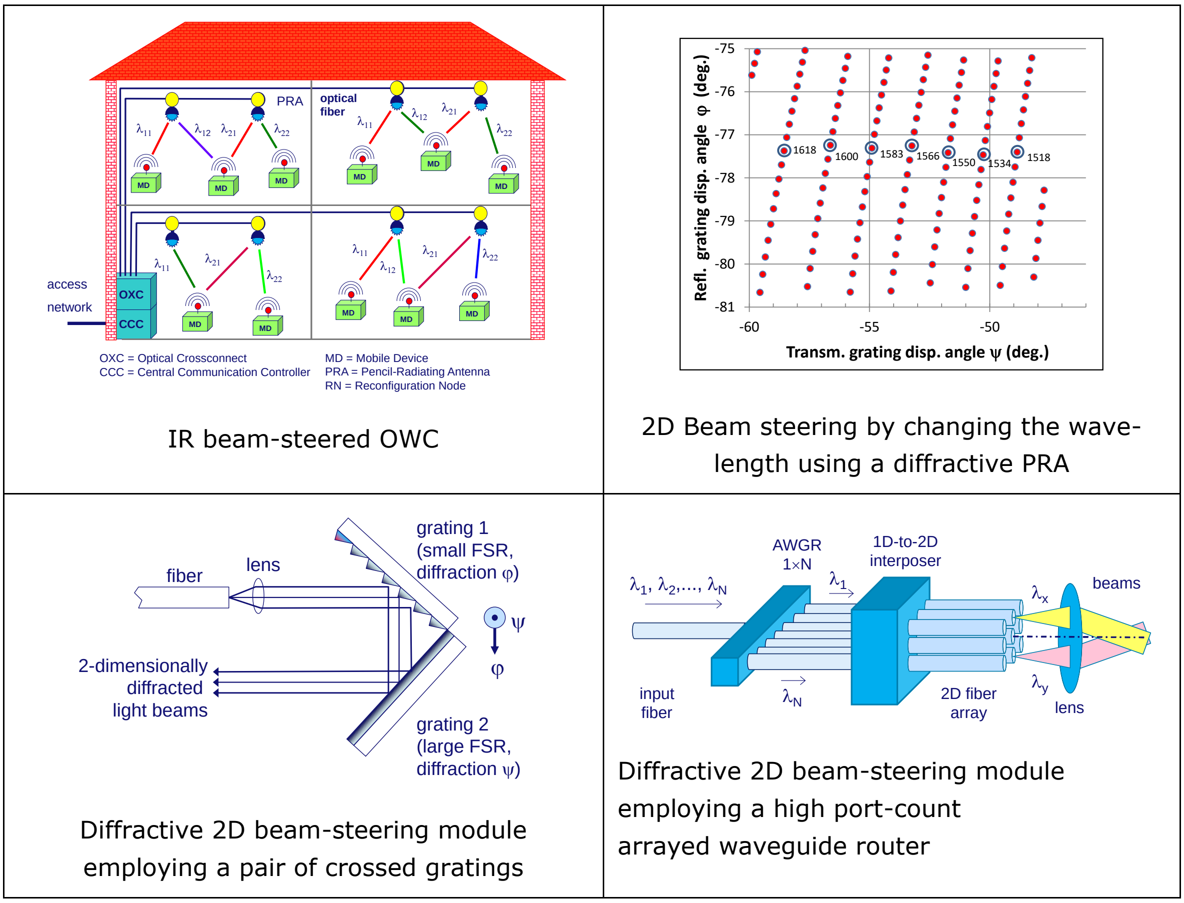


Figure 7: **2D infrared beam steering system using passive diffractive modules and wavelength tuning**

2.2.3 OWC receivers

Being part of the user's device, in all OWC variants described above an OWC receiver should be compact and low-cost, should not require tedious alignment, and should capture enough optical power to enable a high downstream data capacity. Hence it should have a large angle-of-view and a large aperture. However, increasing the active area of a photodetector typically is accompanied by a reduction of its bandwidth, and the etendue principle implies that the aperture times solid angle of view cannot decrease. Fish-eye lenses may be used to enlarge the receiver's field of view, or non-imaging optics such as a compound parabolic concentrator mirror, typically used for solar energy concentration, for enlarging the aperture. A 2D array of fast photodetectors, co-integrated with individual electrical preamplifiers and a summation stage can preserve a large bandwidth while creating a large receiving aperture [23]. Alternatively, the light collection function may be separated from the light detection function, allowing to optimise these functions separately. A wide surface grating coupler (SGC) collecting incident light integrated with a waveguide feeding a fast photodiode can support multi-Gbit/s OOK reception [24]. With an array of SGCs plus an on-chip combiner, the aperture can be extended further without compromising the bandwidth[3].

Device localisation

For beam-steered OWC, localisation and tracking of the user devices is needed[4]. Wifi techniques can be used for this, or 60GHz antenna pattern nulling techniques [25]. Another approach is using IR LED tags at the user device monitored by a cheap camera [26].

2.2.4 Hybrid optical/radio wireless networks

Many network concepts reported so far focus on high-capacity downstream transmission by OWC and provide the upstream path through a different OWC technique with less capacity[5] or by (established) radio techniques. The capacity asymmetry is acceptable in many service scenarios. The upstream path aids connection setup, and for BS-ILC systems also aids device localisation and tracking.

Within the BROWSE system concept [18], this hybrid architecture uses an all optical downlink and a hybrid radio optical uplink. This is implemented with 2D IR beam-steered OWC per room, supported by an indoor flexibly-routed fiber backbone (see Figure 7). Each room has at least two diffractive pencil-beam radiating antennas (PRAs), enabling alternative paths to resolve line-of-sight blocking. The upstream path is done with 60GHz radio over fiber techniques. Using two reflective gratings, 42.8Gbit/s DMT per beam over 2.5m reach has been achieved [27]. An integrated hybrid system has been reported providing 35Gbit/s OOK downstream per λ=1.5μm IR beam over 2.5m with 17deg. $\times$ 17 deg. coverage using an AWGR-driven 2D fiber matrix/lens PRA, and 5Gbit/s ASK upstream plus localisation by 60GHz radio with two high-gain horn antennas on an electro-mechanical tracking stage [25].

Building on optical path reversibility, using carrier recovery all-optical bidirectional 10Gbit/s OOK transmission over 3m was shown [28].

2.3 Interference in (near) visible light spectrum

The penetration of Wifi's radio waves through the walls from neighboring rooms (/houses) may cause interference, and thus adversely impact the radio wireless communication within a room (/house). As a countermeasure, the house owner may install a more powerful Wifi router to overcome the external interference, but subsequently the neighbors may do the same, thus leading to serious radio spectrum pollution in a 'Wifi war'. As (both visible and infrared) light does not penetrate walls, the risk for such escalation is avoided when using OWC.

However, traditionally the (near) visible light spectrum is used for different forms of lighting, both by natural phenomena, such as external lighting by the sun, as by artificial other sources

[3] The etendue constraint may be removed by wavelength-converting the received light and confining it in a fluorophore-doped slab waveguide [29]
[4] Device localisation is not necessary for other OWC techniques.
[5] For example, some OWC products use visible light for the downlink and an infrared connection for the uplink.

such as various artificial lighting sources, computer screens, LED signal lights of other equipment etc. Not only the direct signals from these sources may cause potential interference of OWC applications, but also the indirect signals due to reflection from walls, etc. Additionally some communication applications make use of a part of the infrared spectrum, such as remote controls.

Nevertheless the enormous spectrum range that is available for OWC applications and the relative robustness of the protocols used make the impact of alternative use and users very limited.

2.4 Safety aspects

The effect of laser radiation on the human body depends on its wavelength, power density, and exposure time. The most vulnerable human organ for light exposure is the retina of the eye [30], see Figure 8 [31].

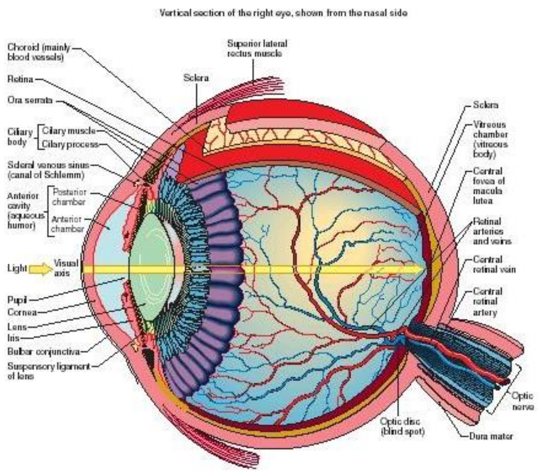


Figure 8: The Human eye (source: http://www.scienceclarified.com)

Laser safety rules comprise the safe design, use and implementation of lasers to minimise the risk of laser accidents, especially those involving eye injuries [32]. Since even relatively small amounts of laser light can lead to permanent eye injuries, the sale and usage of lasers is typically subject to government regulations. Moderate and high-power lasers are potentially hazardous because they can burn the retina of the eye, or (at higher intensity levels) the skin. To control the risk of injury, various eye-safety specifications, for example ANSI Z136 in the US and IEC 60825 [33] internationally, define "classes" of laser depending on their power and wavelength. These regulations also prescribe required safety measures, such as labeling lasers with specific warnings, and wearing laser safety goggles when operating lasers. The eye may be injured by laser radiation in three ways:

- *Photothermally*. Some of the radiation is absorbed by tissue (cornea, lens, retina) and may yield a temperature rise. In the retina, the blood vessels may cool it down; however, at temperatures above 60 deg. Celcius degeneration of the tissue is caused. In the lens cataracts may be caused when proteins in the lens denature.
- *Photochemically*. This effect occurs at high photon energy, such as in ultraviolet (UV) light. The chemical structure of certain tissues may be changed. Such effects occur after a long time of exposure, and also recovery may occur.
- *Photoacoustically*. This effect may arise when high-energy pulses of short duration (<10μs) are used. Significant amounts of energy may be absorbed in such a small time

scale that the fluid in a cell may evaporate fast. The energy thus may give an acoustic shock and may mechanically damage the cellular structures.

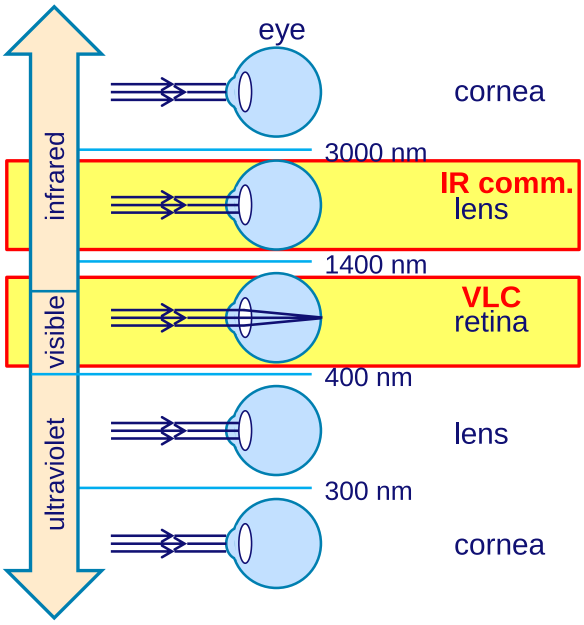


Figure 9: Transparency of the elements of the human eye (source: A guide to laser safety)

The *transparency of the various parts of the eye* is dependent on the wavelength, as illustrated in Figure 9 [35]. Infrared Light communication at a wavelength in the 1.5µm region does not reach the retina, which is the most vulnerable part of the eye, but is stopped at the lens. Optical infrared pencil beams with a diameter beyond 1cm and power <10mW do not provide safety risks for the persons involved. Communication systems using visible light have to comply with existing safety regulations applying to lighting systems, see paragraph 4.4.2. More detailed considerations with regard to potential eye safety issues are described in Annex E.

OWC does not generate electromagnetic radiation that may cause hazards in explosion-sensitive environments, such as in petro-chemical industrial production settings.

OWC also does not generate electromagnetic interference with EM-sensitive equipment, such as used for patient-monitoring in hospital intensive care rooms, and for detecting very weak signals by highly sensitive measurement equipment for physics experiments.

OWC can enable reliable wireless communication in environments which are heavily polluted with EM signals, such as in industrial robot welding streets in the automobile industry.

2.5 Security and privacy aspects

One of the obvious benefits of wireless communication using smaller cells as compared to communication using larger cells is that wireless information is spread over a smaller area: interception of the signal will also only be possible in this smaller area.

Technologies that have difficulty to penetrate walls such as OWC (VLC and BS-ILC) but also Wifi in 60GHz frequency bands are only interceptable in a very small area such as a room. Bundled infrared communication covers even smaller areas, interception is only possible very near the intended receiver or in the direct line of sight between sender and receiver.

Unseen interception of OWC signals will be difficult, however not impossible. Visible light and to a lesser degree infrared signals obviously may be leaking from a room through the windows, and be intercepted by external users. Tests[6] have shown that certain OWC communication can be intercepted from a distance, even from outside with a clever use of optical equipment such as a telescope. Because of its nature BS-ILC is more difficult to intercept out of range of the actual infrared beams. Also, when using BS-ILC, the room's windows may be provided with a coating which passes visible light but blocks the infrared beams; thus privacy can be further improved without affecting the window's daylight admission function. However, as for all communication technologies, security by obscurity should never be the only security measure. Even in a room without windows interception of the signal by equipment in the room still remains a possibility.

OWC solutions for business or consumer purposes should therefore incorporate security measures with regard to authentication and signal encryption in a similar manner as for other wireless technologies. Reuse of existing solutions seems logical, which is illustrated by the choice of the Lifi community to reuse relevant parts of the IEEE 802.11 suite.

2.6 Other ranges and applications

Apart from the aforementioned medium range OWC technology, there are also other ranges for which OWC technology can be adopted. The following will briefly discuss the ultra-short, short, long and ultra-long ranges and the possible applications for the technology therein.

2.6.1 Ultra-short range

Ultra-short range wireless communication is a range commonly used at a chip-sized level and can ideally be used in inter-chip and intra-chip communications. Currently, copper-based electrical interconnections are mainly used to connect chips and logic boards in computer systems and data centers. However, this standard has its limitations like data rates, electromagnetic interference and power consumption [34]. To address this issue OWC technology is being adopted based on an application used in long range wireless communication known as Free-Space-Optical Communication (FSO). This setup allows direct interconnection between chips through a beam of light and it is called Free-Space-Optical Interconnect (FSOI, Figure 10). Even though FSOI is currently still in the research phase early results are promising [36] and it is believed that it may provide a promising long-term solution to the current interconnect problems.

[6] At the ECOC2017 workshop Rafael Perez Jimenez of the University of Las Palmas told that his students had to perform an experiment with the goal to intercept Visible Light Communication through the window of a room using a telescope. The students succeeded in this task. See http://ecoc2017.org/programme/workshops/optical-wireless-communication/ and https://scholar.google.es/citations?user=7dyUaNsAAAAJ&hl=en .

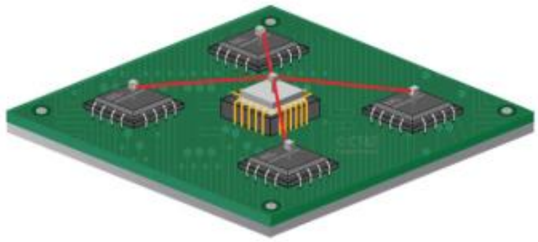


Figure 10: A simple representation of FSOI (source: COST)

2.6.2 Short range

Short range wireless communication uses signals that can travel over distances from a few centimeters to several meters, depending on the technology and transmission power. It is used for wireless body area network (WBAN) and wireless personal area network (WPAN) applications, with the purpose of collecting and transmitting data in the vicinity of an individual. Examples of common applied technologies for these short range applications are Bluetooth, ZigBee, Z-Wave, and IrDA. A typical WBAN setup involves the use of wearable computing devices/sensors, which collect physical and bio-chemical information from an individual and transmit the data to another device [34]. It is an application that has high potential in the healthcare [36], however current common WBANs are Radio Frequency (RF) based, which has certain problems [38]. For instance, RF based WBANs are restricted or even prohibited in medical facilities/hospitals because of electromagnetic interference [34]. Within this context, OWC technology could provide an alternative option to RF based WBANs since OWC does not suffer from the same problems. Currently, optical WBANs (OWBAN) are still being developed and tested for a variety of applications using VLC (Figure 11). Related to OWBANs, optical communication in the form of infrared (IrDA) has been used for WPANs since the mid-90s [34]. It is used to connect various devices in the office like smartphones and printers and new developments for this application are still being developed.

Figure 11: VLC in healthcare (source: postscapes[7])

2.6.3 Long Range

Long range wireless communication can reach distances from 300 meters to circa 10 kilometers, depending on the weather conditions [39]. It is, for instance, applied to building-to-building connections and wireless metropolitan area networks by enterprises and urban markets. Technologies adapting this type of communication are 4G and 5G wireless networks (based on millimeter-wave (MMW)) and Free-Space-Optical Communication (FSO). A typical

[7] https://www.postscapes.com/wifi-lights/

setup would consist of transmitters and receivers on the roof of at least two buildings where a signal is aligned and transmitted between these two devices (e.g., Figure 12). While RF solutions are capable of providing gigabit per second speed as a backhauling solution, FSO is capable of far outshining RF networks with a record speed of 1.6 Tbit/s between buildings. This was achieved by using 16 wavelengths each with 100 Gbit/s [40]. Even though FSO can achieve a faster data rate compared to RF it is recommended to use a hybrid setup if the weather condition has to be taken into account [34]. For instance, if there is a thick fog FSO will not be able to function optimally. In this case the RF solution can take over with a slower data rate until the fog clears.

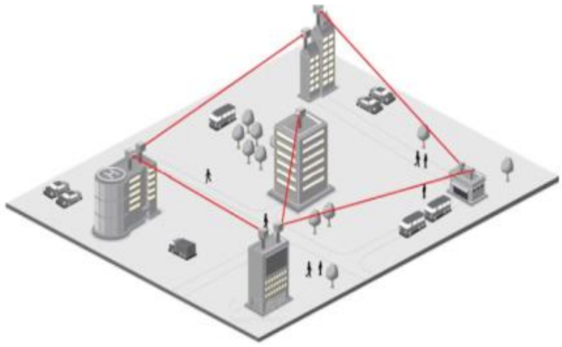


Figure 12: FSO building-to-building (source: COST)

2.6.4 Ultra long range

Ultra-long range wireless communication has reached a distance of circa 84.000 kilometers [39]. This makes it ideal for aeronautical and space communication. To achieve this distance an Optical Wireless Satellite Network FSO (OWSN FSO) communication is applied (see Figure 13). This is similar to the previous mentioned FSO but with a very narrow light beam and a vacuum channel such as in outer space [39]. OWSN FSO has many applications like, space-ground links, space air links, space-space links, and air-ground links [34].

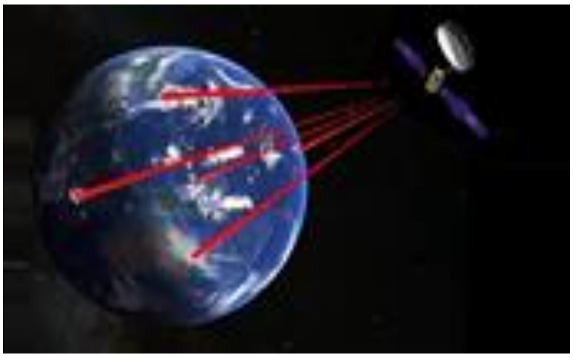


Figure 13: Simple representation of Optical Wireless Satellite Network FSO (source: https://www.sciencedaily.com/releases/2017/06/170615120552.htm)

These ranges all show that optical wireless communication has enormous potential beyond medium range and indoor usage. It shows that the applied methods for one range can be adapted for other ranges with some alterations. Therefore, it is recommended not to limit our focus to a single range, but also be aware of developments in others, which may in the end affect the development of OWC for the medium range.

3 OWC deployment aspects and trends

This chapter briefly describes the deployment aspects and challenges of optical wireless technologies. Assuming that the demand for data intensive applications keeps growing and user devices will continue to facilitate this growth, the main areas of challenges for OWC deployment are:

- The client side of OWC connections: connecting OWC equipment with client devices or incorporating OWC functionality into client devices, as described in section 3.1
- Access networks that provide the capabilities necessary for OWC to be successful, described in section 3.2.
- The network side of OWC connections and the integration in homes and offices of a suitable LAN network that connects with the access network. This is briefly described in section 3.3.

Chapter 4 elaborates further on these aspects from business and regulatory points of view.

3.1 Connection with clients

Evolution from introduction to widespread deployment takes place in roughly two phases, with varying implications for client devices:

Phase 1: OWC as a standalone service

In this phase the OWC solution is likely to be a combination of a peripheral and Access Point(s) that can be plugged in to existing in-building infrastructure.

Table 2: USB speeds (source Wikipedia)

Release name	Release date	Maximum transfer rate	Note
USB 0.8	December 1994		Prerelease
USB 0.9	April 1995		Prerelease
USB 0.99	August 1995		Prerelease
USB 1.0-RC	November 1995		Release Candidate
USB 1.0	January 1996	Low Speed (1.5 Mbit/s)	
USB 1.1	August 1998	Full Speed (12 Mbit/s)	
USB 2.0	April 2000	High Speed (480 Mbit/s)	
USB 3.0	November 2008	SuperSpeed (5 Gbit/s)	Also referred to as USB 3.1 Gen 1 by USB 3.1 standard
USB 3.1	July 2013	SuperSpeed+ (10 Gbit/s)	Also referred to as USB 3.1 Gen 2 by USB 3.1 standard
USB 3.2	September 2017	SuperSpeed+ (20 Gbit/s)	Also referred to as USB 3.1 Gen 3 by USB 3.1 standard

Most peripherals today use USB with supported speeds around 400 Mbit/s (USB 2.0) up to 10 Gbit/s (USB 3.1). Newer versions will support speeds up to 20 Gbit/s [8] (see Table 2). These

[8] https://en.wikipedia.org/wiki/USB/

capabilities are more than sufficient to support the data speeds of the first generations OWC equipment.

Phase 2: OWC as a ubiquitous solution

The first generation of OWC solutions will have limited to no impact in existing devices, products and infrastructure. In the contrary, the OWC solution has to build upon and interface with the existing situation as smoothly as possible, without too much requirements for other products. Many mass produced technology solutions that were originally designed to be offered technically separated from end user devices, eventually ended up in later as integrated parts of later versions of these end user devices. Cameras, microphones and loudspeakers were integrated in laptops, GPS, Wifi and Bluetooth dongles were replaced by integrated components. Therefore, if and when OWC becomes a commodity in a similar way as Wifi, Bluetooth and GPS are now, we expect that OWC functionality will not be regarded a 'separate' product or solution anymore, but will also become an integral part of devices. In that case OWC technology will be incorporated in hardware and software components of almost every device. This will eventually impact a variety of different components, and their suppliers: hardware (optical transmitters and receivers), firmware, device architecture, operating systems and software.

In section 4.1 the connection with clients and these evolution phases will be further discussed from a business perspective.

3.2 Connection with access networks

As indoor user bandwidth keeps growing, access networks able to facilitate these speeds are necessary to keep up with the increasing bandwidth demand. Traditional networks still use copper or coax cables for the last miles but already most of the network, up to street cabinets near the end users, consists of fiber connections. When the demanded higher data rates can no longer be supported by active equipment on both sides of the copper and coax connections, it will be necessary to upgrade also the last meters of coax and copper networks to homes and businesses to fiber connections with high serial bitrate.

These connections may be either point to point fiber connections or next generation passive optical networks (PONs) point to multipoint connections. Theoretically the highest potential datarates can be achieved with point to point connections, as in PON connections multiple endpoints share the capacity of one fiber.

To this point, commercially deployed PON systems are based on time division multiplexed PONs (TDM-PONs[9]). The serial bitrate has been upgraded from approximately 1 Gbit/s to 10 Gbit/s in the past 10 years by two PON standardising bodies, i.e., IEEE [41] and ITU-T [42]. The major challenges in further upgrading the serial bitrate of TDM-PONs beyond 10 Gbit/s, however, are achieving the required optical power budget, the decreased dispersion tolerance and the increased cost of implementation at higher bit rates, especially for the optical network units (ONUs). Therefore, ITU-T abandoned the serial bitrate upgrade path in 2011, and started to work on the other parallel evolution path by stacking multiple 10 Gbit/s pairs of wavelengths, also known as time and wavelength division multiplexed PONs (TWDM-PONs) [43].

In the meantime, there is still a strong interest in researching low-cost implementations at higher serial bitrate for the following reasons. First of all, the total bitrate increase via stacking

[9] TDM-PON is by far the most commonly used variant, but also WDM-PON systems exist.

wavelengths does not come for free. This solution leads to other technical challenges, such as Intra- and Inter-channel crosstalk and rapid frequency drift in the burst-mode operation of directly modulated lasers. Secondly, low-cost tunable optical devices considered in TWDM-PON typically enable limited number of wavelengths. Hence, increasing the transmission bandwidth by further increasing the number of wavelengths in one PON might not be a cost-effective and future-proof evolution path. It has been shown that 25 Gbit/s per wavelength is technically feasible without the needs for any digital signal processing. This is attractive since high volume mature 10-Gbit/s optical parts can still be used when three-level electrical duobinary (EDB) detection or four-level pulse amplitude modulation (PAM-4) schemes are used. In addition, 40 Gbit/s per wavelength transmission has been previously demonstrated as well, using optical duobinary (ODB), PAM-4, and EDB detection, which opens further possibilities to realise 100 Gbit/s PONs [44].

These multiple hundreds of Gbit/s of the next generation PONs will eventually facilitate a seamless connection between indoor and outdoor access networks.

3.3 Integration in home and office

Because OWC can only bridge relatively short distances (up to a few meters) between end user equipment and access points, this has impact on the in-building infrastructure of power distribution to the access points and data connections from the access network termination point to the access points. Figure 14 illustrates the different general options for this infrastructure. Historically, power and data communication use different forms of cabling but newer alternatives can combine both distribution functions.

Apart from the cabling options there are the options to combine or separate OWC as a communication function with other functions. Examples are integration into one product or cooperation with existing or emerging products. OWC solutions can be combined with other functions such as lighting and 'smart lighting' solutions, Wifi access points, sensors etc. In section 4.1 the integration in home and office will be further discussed from a business perspective.

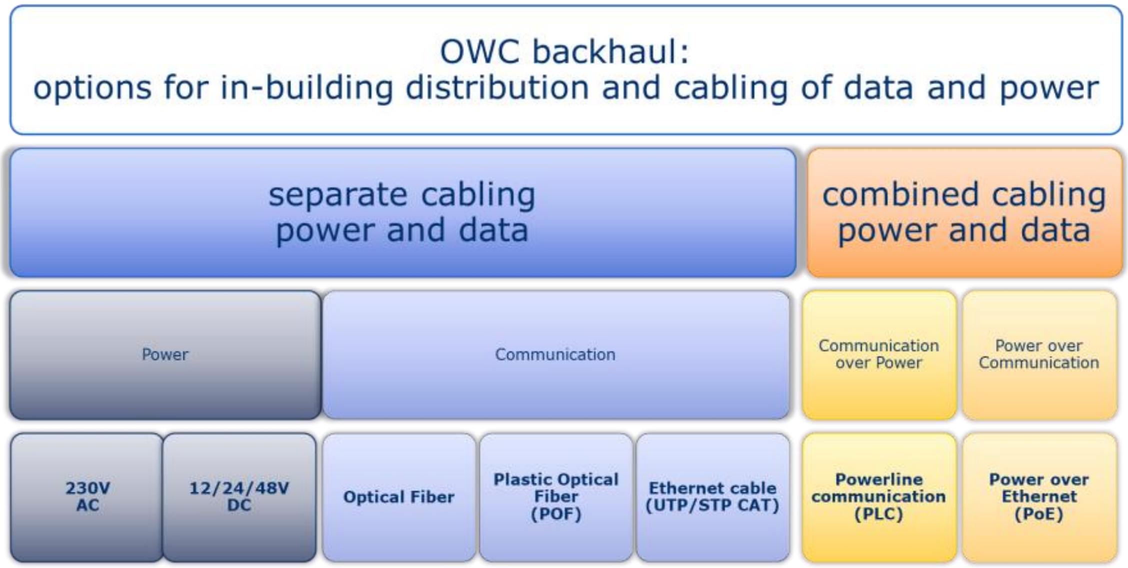


Figure 14: Options for in-building fixed distribution and cabling of data and power

4 Business and regulatory aspects and trends

Optical Wireless Communication is not used as a product in itself but part of a communication value chain. Whether OWC will be preferred solution in certain environments does therefore not only depend on the feasibility of direct alternatives, but also of the other elements in the value chain that directly interrelate with the OWC solution. Section 4.1 discusses the value chain and its evolution, the possible relevant components and market segments. Section 4.2 discusses the potential alternative communication technologies.

4.1 Value chain and market segments

The value chain at first introduction of OWC technology at niche markets, and the relevant components where the solution has to interact with are different from the value chain that will evolve when the use of OWC will become more widespread.

4.1.1 Short term value chain

For the first generation OWC solutions, a complete end-to-end solution is expected to be offered by a single solution provider or manufacturer (see Figure 15). An example is the PureLifi product that is offered today by a limited set of companies.

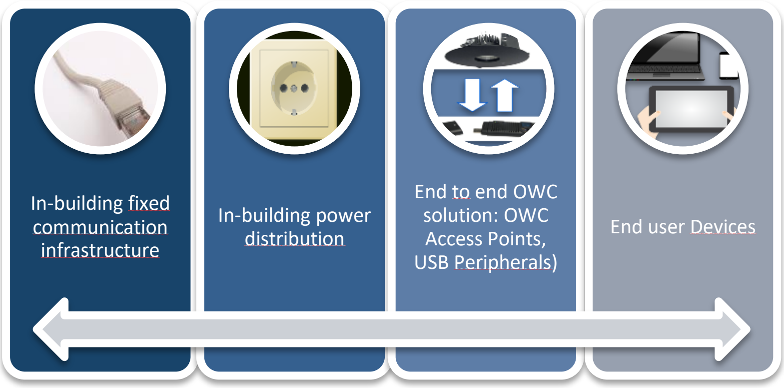


Figure 15: Value chain for Optical Wireless Communication solutions in case of limited scale deployment

Here the access points, end-user device peripherals and coordinating equipment to coordinate handovers are part of one single provider solution. The solution only depends on the in-building fixed communication and power infrastructures and the available interfaces on the end user devices. The data speeds that first generation OWC solutions can process in general can be provided by state of the art infrastructure and end user devices. Some products also support a range of existing LED light fixtures. The Lifi-XC Access Point for instance currently supports both Power Line Communication (PLC) and Power over Ethernet (PoE) options.

4.1.2 Long term value chain

For a next generation OWC solutions to be as successful as Wifi is today, the value chain has to consist of many more components with many associated stakeholders (see

Figure 16).

Figure 16: Long term value chain for Optical Wireless Communication Solutions in case of large scale deployment

Also some components are not necessarily part of the value chain, but may become part of the value chain when businesses around that element see OWC as a business opportunity and their products or services can be of added value. The components and related stakeholders are briefly discussed below:

Access Modems and home gateways: Especially in the consumer market, the access network termination point or access gateway is used by operators to add value. Most modems combine functionality for distributing data, telephony and TV and in most cases are also combined with fixed and Wifi router features. This and potential other functionality such as Wifi public access, 5G femtocell functionality and 'home automation' features may turn the access modem further into a 'home gateway'. OWC may create opportunities for network operators to include OWC functionality into this 'home gateway'.

OWC-LAN of or Wifi OWC-LAN controllers: Primarily in the business market, there will be a need for managing and coordinating OWC access points, and interworking with other network components such as Wifi access points. This will create opportunities for solution integrators.

In-building communication infrastructure and power distribution: As illustrated in Figure 14 several options may emerge for the in-building fixed communication and power distribution infrastructure. Most homes, offices and factory environments currently have a power infrastructure based on 230V Alternating Current (AC)[10] distribution to lighting and power sockets. Ethernet cables (UTP/STP CAT) cables are most common for cabled in-building data distribution to Ethernet ports or Wifi access points.

Data distribution in homes can also be done directly from the access point via Wifi (or via a Wifi repeater but this is very inefficient with regard to spectrum use), or can be done over the electricity distribution network using PLC (power line communication) modems. In theory combining OWC with a PLC solution speeds up to 1 Gbit/s are possible but as the electricity network is used as a shared medium this has to be shared with all users and access points on the network.

Other options are to use optical fiber, which supports very high speeds but is expensive and fragile. Currently it is primarily used for access networks, but in the future it may become also part of the home infrastructure. POF (plastic optical fiber), is a cheaper alternative but does currently not support very high data speeds). See also paragraph 4.2.4. . Most (LED) lighting and office equipment operates on low voltage direct current (DC) and uses AC adapters to transform 230 V AC power transformers to lower Voltage DC power. Battery power and local electricity generation by solar panels also generate DC rather than AC. Also here transformation to 230 V AC power is necessary to use this electricity at home or in the office. All these energy

[10] Except for North America, Middle America and most of South America, Madagascar, Saudi Arabia, Japan and small parts of Asia where 110V AC is most common

transformations are very inefficient. An low voltage DC infrastructure seems a logical next step because it is simpler and more efficient.

Some new offices are now beginning to use low voltage DC cabling for power distribution to lighting, sensors and electrical equipment. However for some applications (servers, routers, but also vacuum cleaners and ovens) it is likely that higher voltage electricity distribution still needs to be in place in parts of the building.

The use of Power over Ethernet enables the combination of data communication and power distribution in one cable for many low energy consuming applications, including LED lighting, sensors and Wifi Access Points. Especially in larger buildings such as offices and industrial environments installing one cabling structure instead of two or more is potentially cost efficient, and also fits in a trend of ‘lighting as a service’ where the amount and color of individual light elements can be intelligently controlled. It can also be used to connect Wifi Access Points to both power and communication infrastructures.

Potential integration of lighting and communication can have many flavours: it may only apply to the infrastructure and cabling, but also to a combination of both functions in one box or even to use the same LEDs for lighting as well as communication. Some interviewed parties claimed that close integration of lighting and communication would create a more efficient infrastructure with higher cost benefits. Other parties believed that lighting and communication functions will remain separate to some degree, because of the totally different requirements with regard to features, but also to maintenance, upgrade and replacement of components.

OWC access points use built in LEDs or external LED lighting for downstream communication (to the end user devices) and an optical receiver for the upstream communication (from the end user devices).

LED drivers or LED circuits are electrical circuits used to power a LED. They must provide sufficient current to light the LED at the required brightness, but must limit the current to prevent damaging the LED. Drivers for high-power LEDs for illumination require complex circuits to achieve correct current regulation[11].

LED lamps or LED arrays do in most consumer products already contain LED drivers but in industrial products they may be offered as separate components.

Large scale deployment of OWC technologies will really get a boost if and when OWC technologies become a commodity and many or all **end user devices** will be ‘OWC capable’ similar to the way that many devices are now are standard equipped with Wifi, Bluetooth and GPS functionality. This not only depends on decisions of the manufacturers of devices, but also on manufacturers of the relevant **chipsets** and (optical) **components** for those devices, as well as developers and producers of **firmware and operating systems**.

Last but not least, **protocols and standards** are needed for interoperability of equipment of most categories described above, and standard organisations need to support evolution, upgrade, maintenance and bug fixing of these protocols and standards.

[11] https://en.wikipedia.org/wiki/LED_circuit

4.2 Alternative or competing technologies for OWC solutions

In this section the alternative or competing technologies for OWC solutions will be discussed.

4.2.1 Wifi

- **Who:** The Institute of Electrical and Electronics Engineers (IEEE) created and maintain the frequency bands used for Wi-Fi since 1997. For this the IEEE 802.11 protocol is implemented containing media access control (MAC) and physical layer specifications for wireless local area networks (WLAN). The certification of devices for Wifi is performed by the Wifi Alliance.

- **What:** The IEEE 802.11 suite is an evolving standards suite for best effort broadband communication over a number of unlicensed frequency bands. It allows - (MIMO) for a number of devices. These bands currently consist of 900 MHz, 2.4, 5, and 60 GHz with different standards (e.g., a,b,g,n,ac)[45].

- **Claims:** The mentioned bands all have their own properties. The 2.4 GHz band was the first band introduced in 1997. Back then it had a data-rate of 1-2 Mbit/s with an indoor range of 20m. Over the years the 2.4 GHz band has improved through new protocol standards (e.g., b,g,n) resulting in a data-rate of up to 600 Mbit/s with a range of 70m. Other bands with higher frequencies (i.e., 5, 60 GHz) can provide the same or higher data-rates over a shorter distance (see Figure 17). For instance the 60GHz band can achieve 6.7 Gbit/s over a distance of 3.3m. It is expected that in 2019 the 60GHz band can achieve up to 100 Gbit/s over a range of 100m [45]. This shows that current properties of Wifi is a snapshot of what a technology is capable of and how much it can improve over time.

  Wifi usage has grown over the years and currently it is said that there are more Wifi devices in use than there are people on Earth, and more than half the Internet's traffic traverses Wifi networks [46]. A probable cause for this division is that Wifi has been integrated in more various devices. Furthermore, devices have become more affordable resulting in multiple devices per user.

  There are hundreds of companies from multiple and various industries collaborating with Wifi Alliance to develop certified devices. This certification drives the interoperability, adoption, and evolution of Wifi globally.

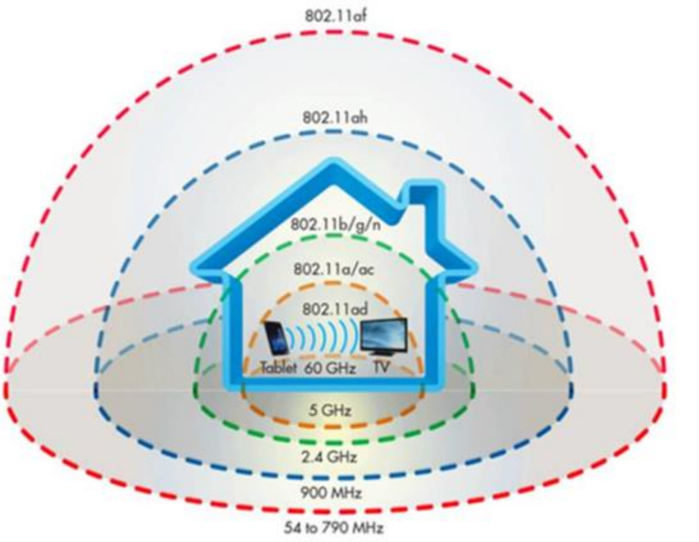


Figure 17: Illustrative and simplified example of Wifi variants and ranges in a typical home (source Ars Technica https://arstechnica.com/gadgets/2016/12/802-11ad-wifi-guide-review/)

- **Status:** Currently Wifi is used in almost every device and according to Wifi Alliance there are more than 35.000 certified products [47]. As mentioned devices have become more affordable, this is because of cheaper components. In addition they are often combined with other standards (e.g., Bluetooth). Adoption or usage of Wifi is further increased because of drivers that are available for all operating systems. Wifi is still growing through new standards that keeps pushing the boundaries of what is capable and through backwards compatibility older devices are still usable.

4.2.2 Wireless HDMI

- **Who:** There are several technologies attempting to become the industry standards for Wireless HDMI, such as the WirelessHD, Wireless Home Digital Interface, and the Wireless Gigabit Alliance. Wireless HDMI follows IEEE 802.11 protocols ranging from the old such as, the 802.11a/b/g/n to the new 802.11ad standard.

- **What:** Wireless HDMI is a term used for wireless high-definition audio and video signals connectivity on consumer devices. In essence, a device will send HD quality audio and video data using unlicensed 5 GHz, 60 GHz or 190 GHz radio frequency, making cables unnecessary. While these devices use unlicensed radio frequencies they all use a proprietary protocol for wireless transmission. For instance Wireless Gigabit Alliance (WiGig) will adapt a HDMI standard that is defined in the IEEE as 802.11ad [48].

- **Claims:** Depending on the technology some wireless HDMI will be capable of supporting 4K resolution in the future [48].

- **Status:** Wireless HDTV is currently an ongoing development.

4.2.3 Bluetooth

- **Who:** For the wireless personal area network (WPAN) a new standard was approved and issued in 2002 and 2005 by the IEEE [49], referred to as the IEEE 802.15.1. This standard is based on Bluetooth technology and similar to the Wifi protocol it defined the specification for the media access control (MAC) and physical layer for WPAN. The body that oversees the development of Bluetooth standards and the licensing of Bluetooth devices is called the Bluetooth Special Interest Group (SIG).

- **What:** IEEE 802.15.1 differs from the 802.11 standard as it is not a standard meant for long distances. This Bluetooth standard is an evolving standards suite, for best effort low energy medium bandwidth communication for a number of unlicensed frequency bands. It uses short-wavelength Ultra High Frequency (UHF) radio waves in the 2.4 GHz band. This short range standard is developed to replace cables between lightweight devices.

Table 3: Bluetooth versions overview (source: Wikipedia)

Bluetooth Version	Maximum speed	Maximum range
1	720 kbit/s	…
2	2 Mbit/s	…
3	25 Mbit/s	10 m (33 ft)
4	25 Mbit/s	60 m (200 ft)
5	50 Mbit/s	240 m (800 ft)

- **Claims:** Since the introduction of Bluetooth in 2002 there have been a number versions released, with version 5 as the latest version. A simple comparison between these versions can be found in Table 3.

- **Status:** Bluetooth is a standard that has integrated into more than 8.2 billion products produced by over 30.000 Bluetooth SIG members, spread over various industries (e.g., Mobile phones, Automotive, Health, and Home Automation) [50]. Like Wifi, Bluetooth consists of cheap components and it is often combined with other standards. The drivers for Bluetooth are available for all operating systems making it user-friendly. The standard is still actively evolving, with the latest version released in 2017, and all versions are backwards compatible.

4.2.4 Fixed access (wired)

- **Who:** Apart from the wireless alternatives to OWC there are also fixed alternatives that are capable of meeting current and future requirements. These fixed infrastructures are bound to certain standards, which are covered by the working group IEEE 802.3 and IEEE 1901. It defines the physical layer and data link layer's MAC of wired Ethernet. These physical connections are made between fixed infrastructures consisting of various types of copper or fiber cables.

- **What:** The following will describe, in short, four fixed infrastructures that are capable of meeting future requirements.

  - Ethernet (CAT-6a/7) cables: commonly consists of twisted pair copper cables. At a distance of 100 meters these cables, depending on the type, can currently reach a transmission speed of 10 Gbit/s with a bandwidth of 500 MHz (CAT-6a) [51]. These cables are most often applied to homes and offices.

- Power Line Communication (PLC, G.hn, Homeplug AV, Homeplug AV2): falls under the IEEE 1901 standard. It uses electrical wiring to simultaneously carry data and power, for applications such as multimedia home networking, audio video, and smart grid. PLC can transmit approximately 500 Mbit/s in LAN applications over a distance of 1500 meters [52].

- Optical Fiber (in building): is made from glass (silica) and it is often used to transmit high data rates over a long distance through a beam of light. However, for in building use the data rate is dependent on the optical unit and the type of fiber installed [51] .This can range from 10 up to 100 Gbit/s.

- Plastic Optical Fiber (POF): is similar to normal optical fiber as it uses light to transmit data. However, instead of using glass (silica) it is, as the name implies, made of plastic and because of this and its thick core (up to 1 mm) POF has a slower data rate ranging up to 1 Gbit/s at present. They are commonly used for short distances up to 100 meters [53].

- **Claims:** In general, fixed infrastructures provide reliable, non-shared, point to point connections. Many fixed technologies evolve and with it higher bandwidths become possible. This can be achieved by upgrading active equipment, improving the cables or making existing infrastructures more efficient. For instance, new categories are being developed for Ethernet cables (i.e., CAT-7a/8) with an expected data rate of up to 100 Gbit/s.

  Furthermore, POF throughput can be improved by using multilevel coding modulations and other spectrum-efficient modulation techniques to approximately 10 Gbit/s [53]. New type of POF such as multi-core and graded-index can further increase its transmission capacity to 40 Gbit/s.

- **Status:** Currently the de facto standard for in-building cabling is Ethernet. It meets the current required speeds and most devices are equipped with an Ethernet connection, which promotes the ease of use. Fiber cables are mostly used as a means to transport information over long distances. It often stops when it reaches the house and after that it is handed over to an alternative connection. Power over Ethernet or PoE is a convenient way of transmitting data throughout the house, without additional cabling. Even though it currently isn't capable of providing Gigabit speeds it does has a feature that other connections do not have, namely transport of electrical power. This additional feature of PoE holds the potential to complement the use of OWC, since it can transport enough power for LED fixtures.

4.2.5 5G pico- and femtocells

- **Who:** 3GPP is a collaborative work between groups of telecommunication associations founded in December 1998. Their goal was to create a globally applicable technical system that is based on the evolution of third generation GSM networks and its radio technology. The 3GPP working groups are responsible for the specifications of the network protocols and the infrastructure of GSM, GPRS, UMTS and LTE networks. The support for 5G is currently being developed and discussed with a planned release of early 2020.

- **What:** With the development of smaller cells (e.g., atto-, femto-, pico-, and microcells) it is possible to provide a better in-building coverage using licensed spectrum. A disadvantage is that spectrum is licensed per operator and also currently networks and network and network equipment is distributed per operator. But theoretically more infrastructure sharing could be possible between network operators[12] and there is a growing demand for full indoor coverage of mobile networks. This together with an 'unlimited' data bundle it is feasible that one would use a mobile network as main network for their data needs. Especially when there is no good alternative available in or around the house. Current 4G LTE Advanced standards can deliver a data-rate of circa 100 Mbit/s.

- **Claims:** With the future release of 5G it could be possible to reach a speed of up to 10Gbit/s.
- **Status:** At the moment this is still evolving and network components need to be released on the market first.

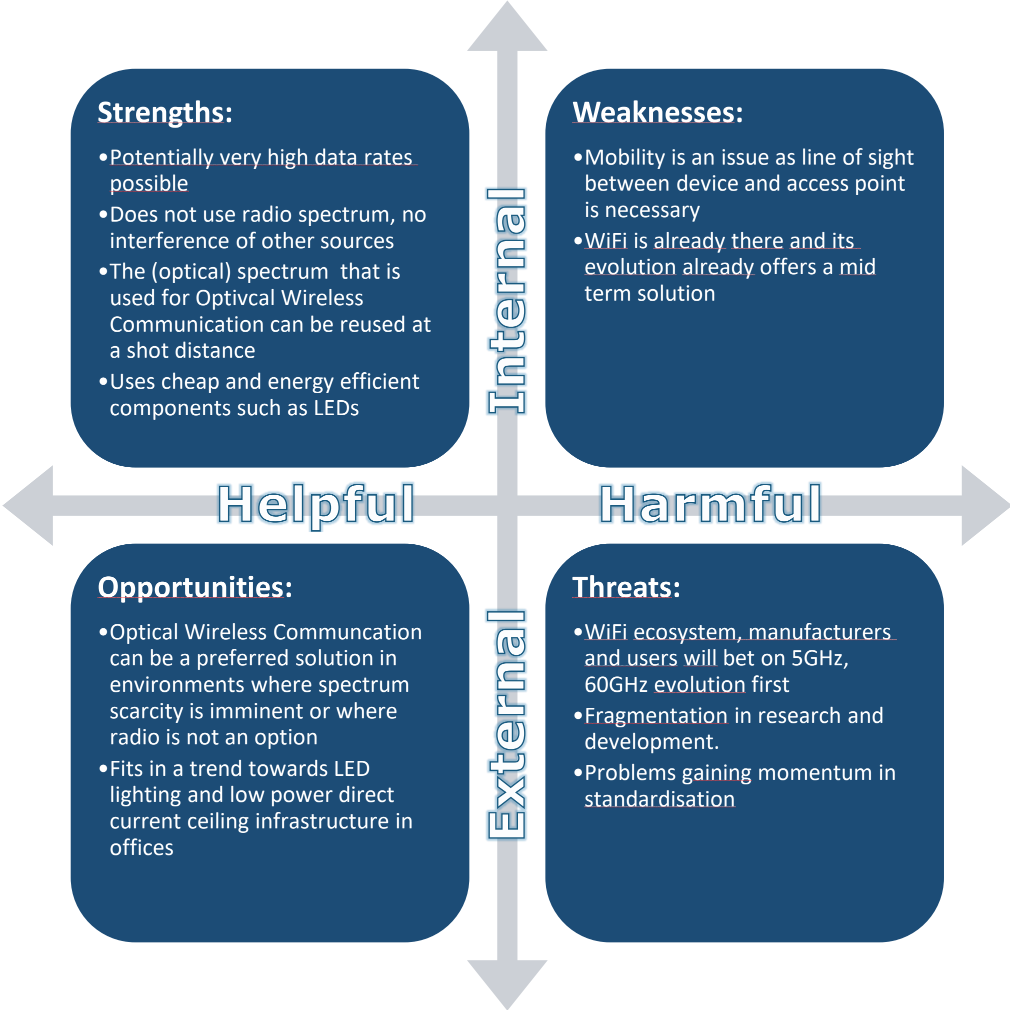
4.3 Issue analysis: enablers and barriers

4.3.1 SWOT analysis on technologies and OWC in general

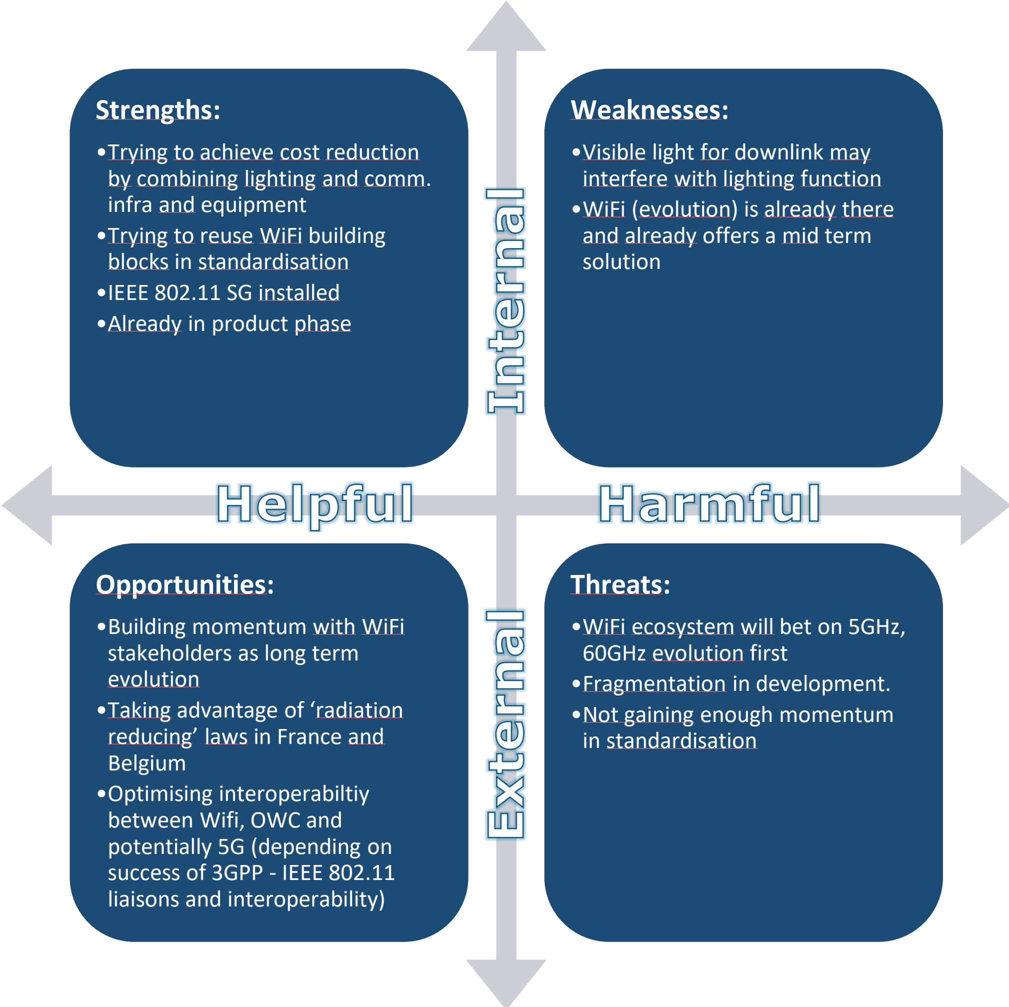
In this section we look at the main Optical Wireless Technology options in relation to potential alternatives and assess their evolution prospects in a brief SWOT analysis per technology. In Annex C additional SWOT analysis matrices can be found for other optical wireless technology variants and for a number of alternative wireless communication alternatives.

[12] In some situations (tunnels, shopping centers, railway stations, airports, parking garages etc.) some coordination is already inevitable.. The situation around Infrastructure sharing between operators varies per situation and per county. See also: https://en.wikipedia.org/wiki/Telecom_infrastructure_sharing. Also in some cases regulations regarding indoor coverage and accessibility of emergency services require DAS installations etc

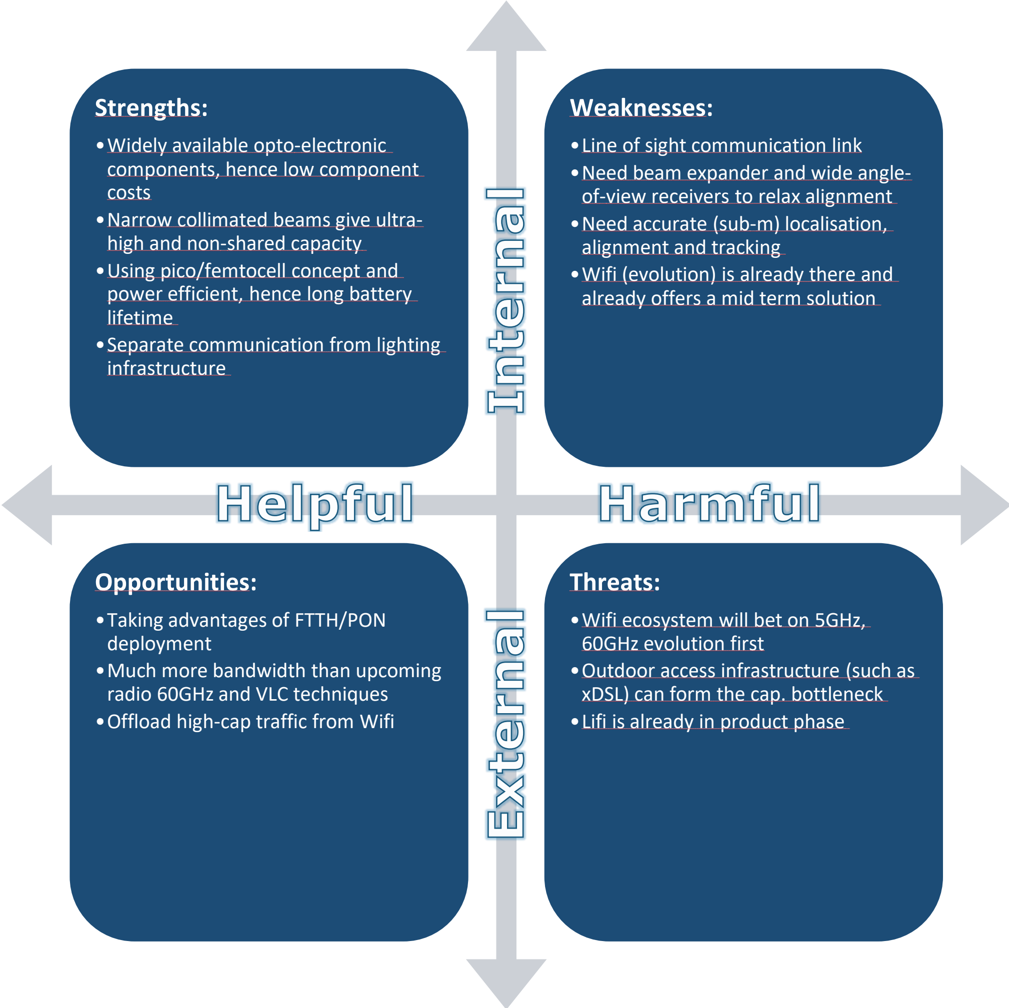
4.3.2 General Optical Wireless Communication SWOT matrix



4.3.3 Lifi SWOT matrix



4.3.4 ILC SWOT matrix



4.3.5 Issue Map

Based on the deployment aspects described in chapter 3, the observations with regard to evolution of the value chain, other relevant factors described in this section, and additional sources [54] [55], an 'issue map' can be made that briefly summarises the main issues that OWC evolution will face. In Figure 18 first a breakdown of the most important components of the value chain is shown, with the main issues and per issue the main options, sub options, or sub issues.

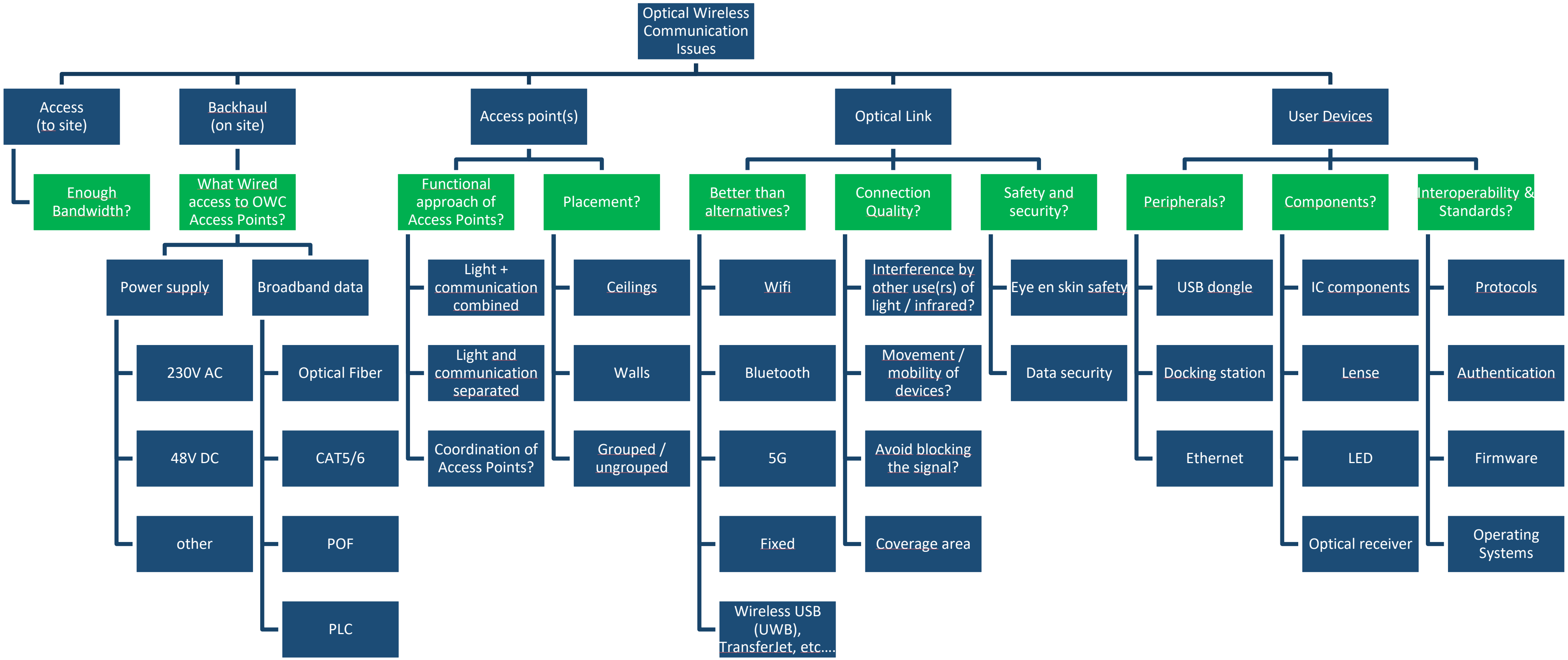


Figure 18: Optical Wireless Communication issue map

4.4 Standards, regulatory and legal aspects

In this section aspects and trends impacting OWC development and deployment are described with regard to standards (section 4.4.1) and regulatory and legal aspects (section 4.4.2).

4.4.1 OWC Standards

As the user base grows, interoperability becomes more important. Standards provide the theoretical basis for interoperability but have to be developed, supported and maintained by companies that are actually implementing and using standards in their products to become practical. Historically successful standards emerge from a de-facto standard that is pushed by a powerful supplier or by active standards organisations, mostly supported by multiple suppliers, defining interoperable, and living standards. Successful standards can have impact on a variety of products and stakeholders, also on those that do not seem to be directly related to OWC.

Several standardisation initiatives for indoor high speed optical wireless communication have emerged [54].

Infrared Data Association IrDA

In the 1990s and early 2000s infrared communication between laptops, PDAs etc. was relatively popular as it could provide relatively high data rates over short distances. It was standardised by a group of manufacturers in the Infrared Data Association IrDA[13] and built in as a standard component in many devices. When Wifi and Bluetooth became more popular and able to support higher data rates the technology was no longer built in and supported. The fastest variant is **GigaIR** which supports speeds of 512 Mbit/s to 1 Gbit/s over distances of several meters. The standard is not widely supported anymore, but equipment is still used in some environments where interference makes radio-based wireless technologies unusable. The IrDA website mentions the creation of a new Working Group to accomplish 5 and 10 Gigabit Optical Wireless Communications in 2011 as its most recent news item. Revival of this standard suite is not likely.

IEEE

The Institute of Electrical and Electronics Engineers (IEEE) is working on optical wireless communication standards in two working groups:

IEEE 802.15 is a working group of the IEEE 802 standards committee which specifies wireless personal area network (WPAN) standards. Within this working group Task Group 7 (TG 7) focusses on optical camera communications which can provide low to medium data rate OWC communication and free space optical communication systems (building to building). Task Group 13 (TG13) defines standards for Multi-Gigabit/s Optical Wireless Communications (IEEE 802.15.13).

Supporting and contributing organisations in this groups successfully promoted this technology to be updated and incorporated in IEEE 802.11, to be able to reuse parts (such as authentication and encryption mechanisms) of the 802.11 stack and to support maximum interoperability between Wifi and OWC technologies on user devices.

[13] http://www.irda.org/

If single sign-on[14], roaming and handover mechanisms can be optimised and integrated this may eventually create a more fluent end user experience with optimal mobility for the user, with equipment automatically using the most optimal connection technology available in a situation: OWC when available and wifi when the line of sight with OWC access points is lost. Because 802.11 and 3GPP are also slowly moving towards endorsement and interworking[15] of each other's protocol suites, OWC integration in the 802.11 suite may even provide an opportunity for future interworking with mobile (5G and beyond) protocols.

IEEE 802.11 is a working group of IEEE 802 standards committee for the wireless Local Area Network standards commonly referred to as 'Wifi'[16]. In November 2016, IEEE has formed a Topic Interest Group (TIG) to start activities of Lifi standardisation, In July 2017 a Study Group 802.11 Light Communications (LC) was formed. This group currently works on use cases and usage scenarios. The start of a potential LC task group that will define actual standards is planned for May 2018.

ITU

Within the International Telecommunication Union two study groups work on optical wireless communication related documents:

ITU-R study group 1 ("Spectrum Management") is working on a general study on Optical Wireless Communication in response to ITU-R Question 238/1. This report may provide input for this study. Current status is a Preliminary Draft New Report, which is planned to be completed in 2018.

ITU-T study group 15 ("Networks, Technologies and Infrastructures for Transport, Access and Home") started studying indoor high-speed visual light communication systems (100 Mbit/s to 1 Gbit/s), including general characteristics, wavelength band plan, architecture, interfaces and protocols in the G.hn standard. The current G.hn standard defines Power Line Communication protocols, which could potentially ease the interworking of OWC with in-building Power Line Communication (PLC) solutions.

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[14] This may even provide opportunities for federated sign on mechanisms such as eduroam and govroam.
[15] http://www.3gpp.org/news-events/3gpp-news/1771-wlan_lte
[16] The IEEE does not test equipment for compliance with their standards. The 'wifi alliance' was formed to certify interoperability of IEEE 802.11 based products (https://www.wi-fi.org/)

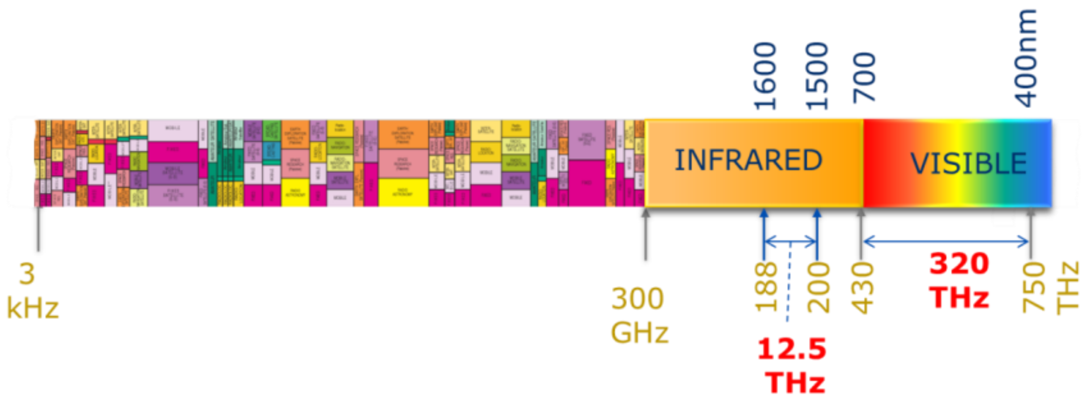

Figure18: OWC offers huge extra spectrum (2600x size of available radio spectrum): Radio spectrum regulated (source: Joanne Oh, PhD defence Mar. 9, 2017)

4.4.2 Regulatory and legal aspects

As Figure 18 illustrates, spectrum regulation and frequency allocation by national governments and the ITU roughly covers the spectrum between 3kHz – 300MHz ("radio") and 300 MHz - 300 GHz ("microwave"). The EC Electromagnetic Compatibility directive [56] does not seem to specifically state that is only applicable up to a maximum radio frequency. However, it refers to a directive regarding radio equipment [57] that does state "'radio waves' means electromagnetic waves of frequencies lower than 3000 GHz, propagated in space without artificial guide;". The spectrum between 300 and 3000 GHz is sometimes called 'Teraherz waves' and sometimes 'low infrared', depending on background and argumentation of the source. Radio spectrum above 3000 GHz is generally referred to as 'infrared' and above 430 THz as 'visible light'.

One can assume it is not feasible to expect the directives to apply in infrared and visible light spectrum. Although indirectly all kinds of regulations apply regarding for instance lighting and heating, these frequency bands are de facto a greenfield with respect to regulatory aspects concerning communication and it might be assumed it to remain spectrum-"unregulated". This part of the spectrum is heavily influenced by phenomena such as natural light and radiation and reflection of dead materials and living bodies.

The regulations that do apply mainly are concerned with health issues, in particular with regard to intensity and burstiness of radiation.

Intensity

The effect of light or infrared radiation on the human body depends on its wavelength, power density, and exposure time. As described in 2.4 and Annex E the most critical human organ is the eye. OWC solutions in the Netherlands should be compliant with safety regulations such as NEN-EN-IEC 62031 (Led modules for general lighting – Safety specifications) [58], an umbrella standard that includes NEN-EN-IEC 62471 (photobiological safety of lamps and lamp systems) [59]. This document describes amongst others the risk classification categories with regard to optical radiation as illustrated in Table 4. Most of the LED products are expected to fall under Risk Group 1 (low risk) but some interviewed parties express concern that some of the current LED equipment for outdoor and also indoor use falls under Risk Group 2 (Moderate-Risk). Here special care with regard to installation and maintenance personnel is advisable.

Table 4: Risk classification according to NEN-EN-IEC 62471

Risk Group	Philosophical Basis
Exempt	No photobiological hazard
Group 1 (Low-Risk)	No photobiological hazard under normal behavioral limitations
Group 2 (Moderate-Risk)	Does not pose a hazard due to aversion response to bright light or thermal discomfort
Group 3 (High-Risk)	Hazardous even for momentary exposure

Identifying, classifying and constraining optical radiation risks in labor environments [60] becomes more important when LED and OWC solutions become more widespread. Also OWC solutions deploying infrared laser beams should conform to eye safety standards such as the ANSI Z-136 series and IEC 60825-1 series.

Electrical equipment

Necessary backhaul and power supply for access points need to comply with NEN 1010 (Electrical installations for low-voltage - Dutch implementation of the HD-IEC 60364-series) [61] and NEN 3140 (Operation of electrical installations - Low voltage) [62]. These regulations apply to for instance ensuring that it is clear whether equipment is switched on (to minimise electric shock risk). It is not always clear whether current LED lighting systems are compliant with these standards, especially with regard to maintenance, as the necessary communication backhaul and power supply for OWC access points need to be safe to install, inspect and maintain.

Burstiness

Also there are some regulations with regard to burstiness and stroboscopic behavior of light emitting sources. Equipment vendors have to ensure some protection measures with regard to epileptic sensitivity [63].

Shared use for communication

Currently no known regulations apply with regard to allocation, licensing or duty cycle of usage for shared or concurrent communication purposes. Some “de facto” spectrum allocation for infrared is in place[17], without regulation but just because of certain characteristics of components or certain decisions of product manufacturers. As OWC solutions can be easily made robust with regard to other use, users and natural phenomena and there is a very high amount of theoretically available spectrum, currently there seems to be no need for additional regulation. Also in regulation of radio spectrum there is a trend to limit application specific spectrum allocation. Regulation, certification and licensing may even slow down innovation. It remains however important to ensure safety restrictions, also in environments with multiple light or infrared sources.

[17] Such as the infrared spectrum around 870 nm and 930–950 nm for remote controls, see https://en.wikipedia.org/wiki/Consumer_IR and https://en.wikipedia.org/wiki/Remote_control

Legislation with regard to other wireless communication solutions

In some countries national or local legislation is in force with regard to the use of Wifi or mobile equipment close to children. This may create an opportunity for wireless communication solutions not using radio spectrum. See also section5.2.

4.5 Stakeholder analysis

Many stakeholders are involved or potentially involved with the research, development, evolution, deployment and use of optical wireless communication solutions.

Table 5: Identified OWC Stakeholder types and examples

Stakeholder type	Sub Category	Examples
Access Network community		
	Infrastructure equipment providers and integrators	Ericsson, Nokia
	Access service providers	Ziggo, KPN
Indoor communication community		
	Access Points and driver manufacturers	Rocade, Cisco, HP
	WiFi Controllers	
Communication integrator community		
	Equipment coordinating Handovers Lifi / Wifi	
	Single signon: Eduroam / Govroam, WPA enterprise	
	WPA enterprise solutions	
Lighting community		
	Fixtures (Luminaires)	
	Lamps	Philips, Osram, Zumtobel
	LED drivers	
	Lighting as a service, ambient lighting solutions etc.	Philips, …
Components (hardware, software)		
	Silicon / IC	NXP, ASML
	Silicon production	ASML
	Supporting software, Operating systems, drivers, etc.	Microsoft, Google, Apple, …
	peripherals	Logitech, Netgear, TPLink, kijk naar PLC fabrikanten en Wifi plugins
Standards and regulation community		
	standards organisations	IEEE, ITU-T
	Certification organisations	WiFi alliance, …
	Governments, regulators, health certification, …	
Building installation community		
	installation, integration	UNETO, KIEN
	power sockets power lines	PLC, POF
Consumer devices community		
	General purpose devices (smart phones, tablets, laptops)	Huawei, Samsung, Apple, ….
	consumer TV smart TV	
	Specific devices (photo cameras, video cameras, navigation systems, game consoles	

Several sources were combined to identify and categorise the relevant stakeholder types: the components of the value chain that are described in section 4.1, a general overview with examples that was made during the desk research stage of the project (see

Table 5), and an overview that was made at a workshop with stakeholders and experts in October 2017 at the Eindhoven University of Technology as part of this project (see Figure 19). In this overview also a categorisation was attempted with regard to urgency (stakeholders that need OWC solutions), power (stakeholders that can provide OWC solutions or parts thereof), enabler (stakeholders that are necessary for OWC solutions to be successful, accelerators or enablers), and legitimacy (stakeholders that are mandated or legitimised to play a role).

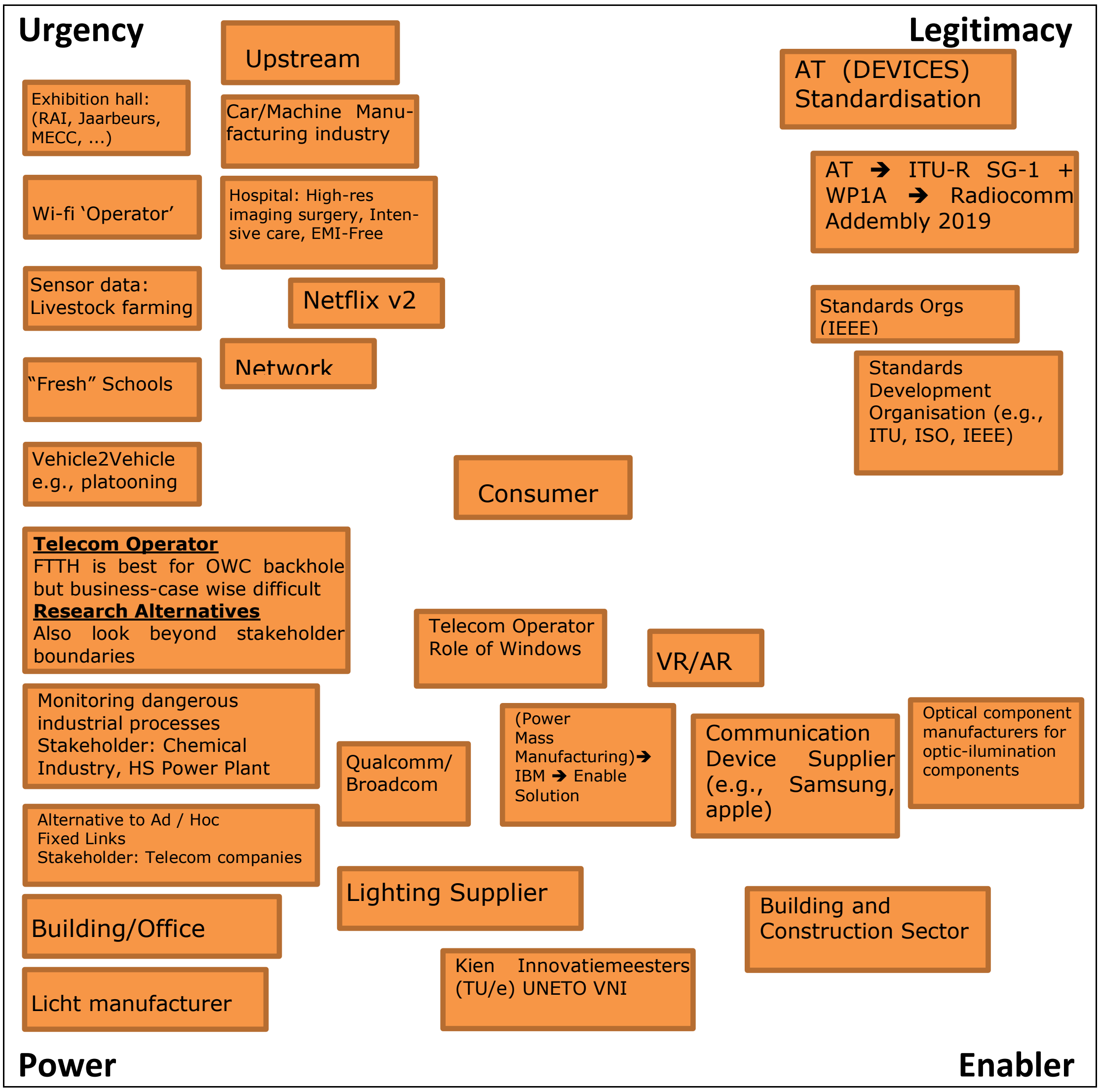

Figure 19: Inventory of potential stakeholders by experts during the workshop held on october 11th 2017.

For further combination and analysis of this input the work of Mitchell et al. [64][65] is used, where three attributes are distinguished for analysis of stakeholder roles and their actions:

- *Power*, defined a as relationship between stakeholders where one stakeholder A can get another stakeholder B to do something that B would not have done otherwise;
- *Legitimacy*, defined as generalised perception that actions by a stakeholder are 1appropriate within a system of norms;
- *Urgency*, the degree to which stakeholder claims call for immediate attention.

Pressures from stakeholders are more successful if these stakeholders accumulate the attributes. Stakeholders with all three attributes ('definitive stakeholders') are considered most effective in getting their priorities accepted. The identifications 'Definitive stakeholder', 'Dominant stakeholder', 'Demanding Stakeholder', etc. in a stakeholder typology diagram (such as depicted in Figure 20) provide a description of likely or potential general behavior of the stakeholder. Although it is not always possible to define the stakeholders on an equal level, the diagram gives an idea about the perception of the position of the relevant players, and can provide insight into their acts or can visually represent their perceived roles.

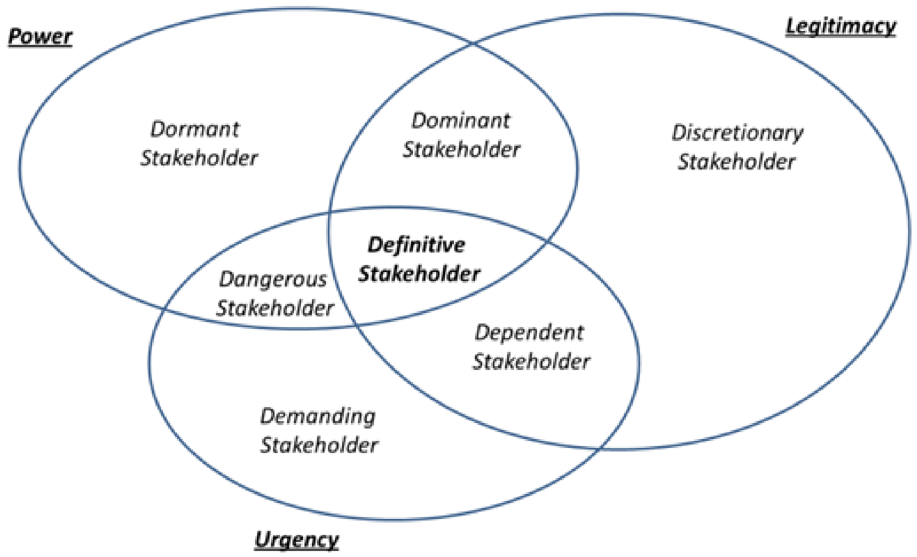

Figure 20: Stakeholder typology (from Mitchell, R.K., Agle, B.R. , and Wood, D.J. (1997) "Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts", Academy of management review, pp. 853-886. p. 874)

The resulting stakeholder types and their position are depicted in Figure 21. Manufacturers of device peripherals, OWC product manufacturers and OWC researchers are considered at this moment the most definitive stakeholders that combine power, legitimacy and urgency with regard to OWC development. End users do not currently experience the need for OWC as a solution. When spectrum scarcity becomes more apparent, urgency to be involved in OWC grows for certain (high end) content and application providers and for some user groups that represent specific environments were the scarcity is most problematic, such as sport stadiums and hospitals.

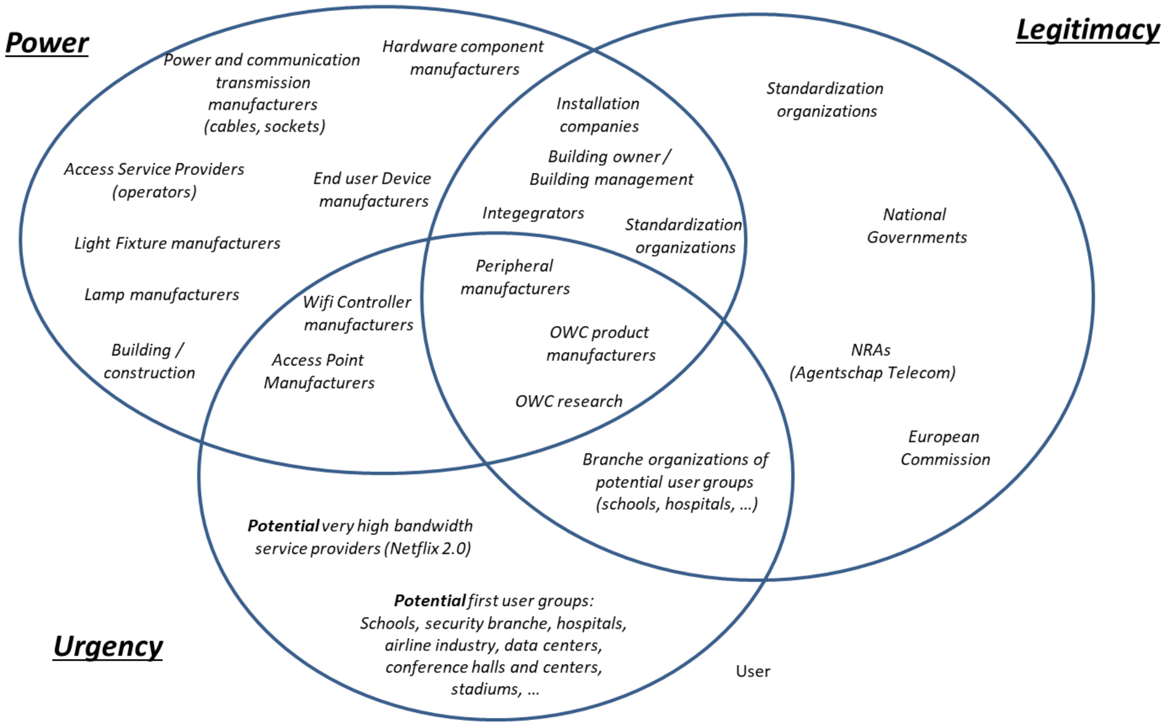

Figure 21: Analysis of OWC stakeholders, using determination of stakeholder typologies a combinations of stakeholders with power, urgency and/or legitimacy (using methodology from Mitchell, R.K., Agle, B.R. , and Wood, D.J. (1997)

OWC development can benefit by bringing together the (potential) definitive, dominant, dangerous and dependent stakeholders to interact and communicate. Initiatives such as the VLC workshop organised by the Radiocommunications Agency before and during this project and the KIEN innovation tables to investigate the potential of OWC for schools[18] may help to focus and grow interest in OWC research, development and deployment.

[18] https://kieninnovatiemeesters.nl/projects/frisse-school-en-een-razendsnelle-data-omgeving/

5 Main trends and options

Wireless broadband access has become a commodity. Moore's law and consumer behavior lead to a virtuous circle: networks and equipment are capable of transporting more and more bandwidth leading to development of applications that use higher data rates and users that use these applications at more different places for longer periods demanding even better and more ubiquitous broadband access.

Four major trends can be distinguished that also influence each other:

- Evolution of existing radio technologies toward smaller cells;
- The need to upgrade and densify the in-building fixed communication distribution;
- Trends in lighting towards very energy efficient and connected;
- Power distribution is shifting towards low voltage DC power.

These trends are described in the first four sections of this chapter. In the second section examples of existing and emerging OWC products for high bandwidth indoor use are given and some user group initiatives are discussed. In the final section general options for the future of OWC are discussed.

5.1 Trends with impact on OWC development and deployment

5.1.1 Evolution of existing radio technologies towards smaller cells

The increase mentioned above is described in "Cooper's Law" by Martin Cooper (Figure 22), leader of the research team that developed the mobile phone at Motorola. The law states that the maximum number of calls or an equivelant amount of data that can be done using all available radiospectrum at a certain place, will double every 30 months. Cooper discovered that the ability to perform simultaneous radio communications at the same place and time is growing at the same rate since the first broadcast conducted by Marconi in 1895 [66].

Figure 22: Martin Cooper (source: Wikipedia)

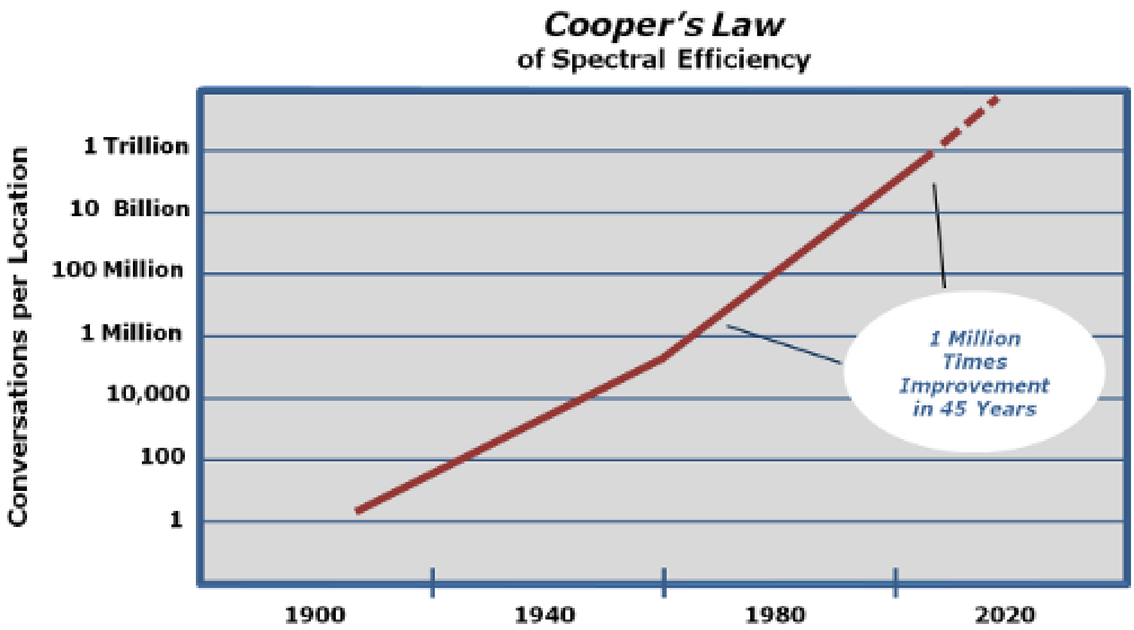

Figure 23: Cooper's law of spectral efficiency: the number of conversations or equivalent equivalent data transactions that can be conducted in all of the useful radio spectrum over a given area doubles every 30 months. (source: www.arraycomm.com)

In the past 45 years the spectrum efficiency has improved 10^6 times, see Figure 23. It is often assumed that this is mainly due to technical innovations. However, Cooper claims this is only partly true:

- A factor of 5 is due to improved division of the frequency spectrum in bands (frequency division).
- Another factor of 5 is due to the development of increasingly better modulation techniques (e.g., FM, SSB, QAM etc.).
- But by far the largest factor, by a factor of 1600, is due to the use of the same spectrum in different places (smaller cells).

With the technological developments and standardisation of 5G, the possibility of getting smaller cells is further facilitated, resulting in future generations of mobile networks that can continue to facilitate the increasing demand. Also development in active equipments play an important role, in addition to, the developments in the radio layer and using multiple antennas or installation points (e.g., CloudRAN, MIMO, Massive MIMO, beamforming, self optimising networks, smart handover techniques) and various backhaul options (e.g., fixed, microwave link, femto cells over Internet, but also techniques like meshed routing, swarm and ad-hoc routing can provide different perspectives on the access possibilities for smaller cells) [66].

Higher spectrum bands and smaller cell sizes for wifi and mobile technologies

Continuing growth of use of wireless devices and processing of growing volumes of data at higher speeds claim more and more radio spectrum. Main examples are the growing use of high quality video streams and the rapidly emerging and growing 'Internet of Things' applications [67]. Applications make more and more use of higher frequency bands. Higher radio frequencies allow for higher data speeds but are also less capable of propagating through or around dead and living material. Communication over higher frequencies generally is more vulnerable for atmospheric conditions and needs 'near line of sight' for optimal performance. In general higher frequency bands are used for smaller cells or very focused point to point communication (microwave beam shaped links[19]). The disadvantage of its limitations is also an advantage as with higher frequency bands it is easier to reuse the same frequency band in another location with minimal interference.

The 5 GHz band is currently available for license exempt use and is mainly seen as the band to relieve the crowded 2.4 GHz band for wireless broadband (using 802.11n/ac, allowing wider channels up to 160 MHz). The expected usage mainly involves high-bandwidth applications, although Wifi enabled IoT applications might also use this spectrum.

Restrictions related to military use and radars apply for (a large) part of this band. This limits the flexibility of devices and products in this band. In practice this means that to use the entire band a dynamic frequency section or DFS-system that switches away from a part of this band if radar is detected is mandatory in access-points.

Even for professional users it is not always clear what the chances are that temporary or permanent unavailability of spectrum due to DFS obligation will occur. Providing better information about the (expected) availability in place and time[20] throughout the Netherlands could help removing this barrier in some cases. Other parts of the band are restricted to in-door use only. It is unclear whether enforcement of this restriction is feasible, especially for the growing numbers of consumer devices that are also used outside.

The potential use of 60 GHz spectrum (57-66 GHZ in Europe[21]) has gained attention recently and is being considered for high-bandwidth, short distance communication. This is mainly driven by proposals for wireless multimedia-streaming within a room from for example a home theatre PC to the TV, eliminating the need for Ethernet-cables around the TV. Proposed protocols include 802.11 ad and WirelessHD both aiming to provide data rates of multiple gigabits per seconds over short distances. Although bands vary slightly throughout the world, there is a large overlap of 5 GHz of harmonised bandwidth worldwide.

Also newer generations of mobile communication technology (such as 4G and, 5G) enable and promote the use higher frequency bands (such as 3500 MHz) and smaller cells to facilitate higher data transmission speeds in areas with a high user density.

In general lower frequency bands and larger cells are used for cases where mobility is important and higher frequency bands and smaller cells for cases where capacity is needed and mobility is less important. As Figure 24 illustrates, using much higher frequency bands and providing much higher data speeds over even shorter distances, optical wireless communication theoretically fits perfectly in this trend.

[19] https://en.wikipedia.org/wiki/Microwave_transmission

[20] For example, the likelihood that part of the spectrum is not available depends on the presence of radar systems using that frequency. In locations where radars are expected, this might pose a problem, while in other locations it might not. An indication of the (expected) percentage of time spectrum that cannot be used at some locations would potentially help.

[21] For an overview see http://www.digikey.com/en/articles/techzone/2013/jul/high-speed-60-ghz-wireless-connectivity-finally-takes-off

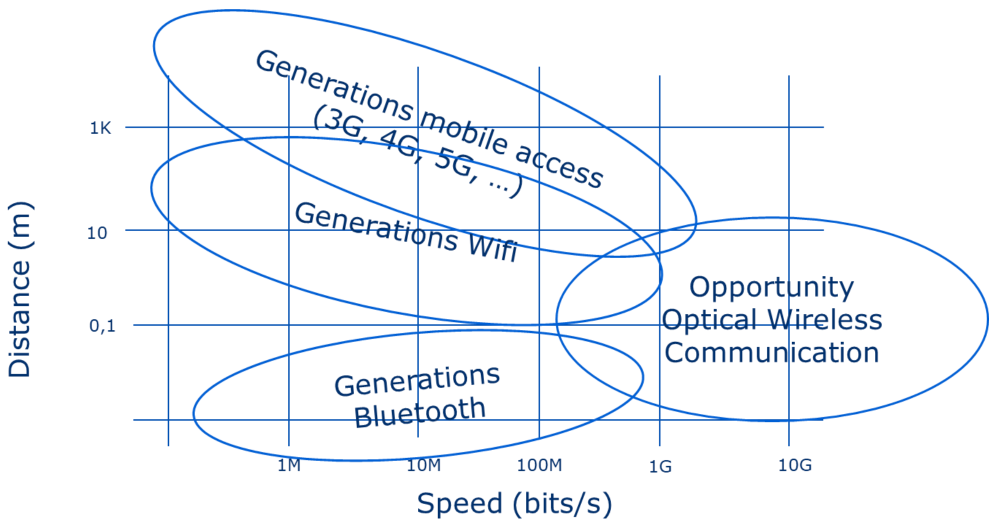

Figure 24: Potential OWC and coexistence: evolution of existing wireless technologies moves towards higher data rates over shorter distances

5.1.2 Lighting moves towards 'energy efficient' and 'connected'

Traditionally, office lighting consisted of Fluorescent lights (TL) but because of the price drop and increased energy efficiency of LED lighting this type of lighting is installed more and more in offices and homes[22].

More and more this is combined with intelligent management of the lights, combining lighting with sensors (movement, outdoor light) and the ability to change or adapt lighting schemes and coloring throughout rooms and buildings at any given moment.

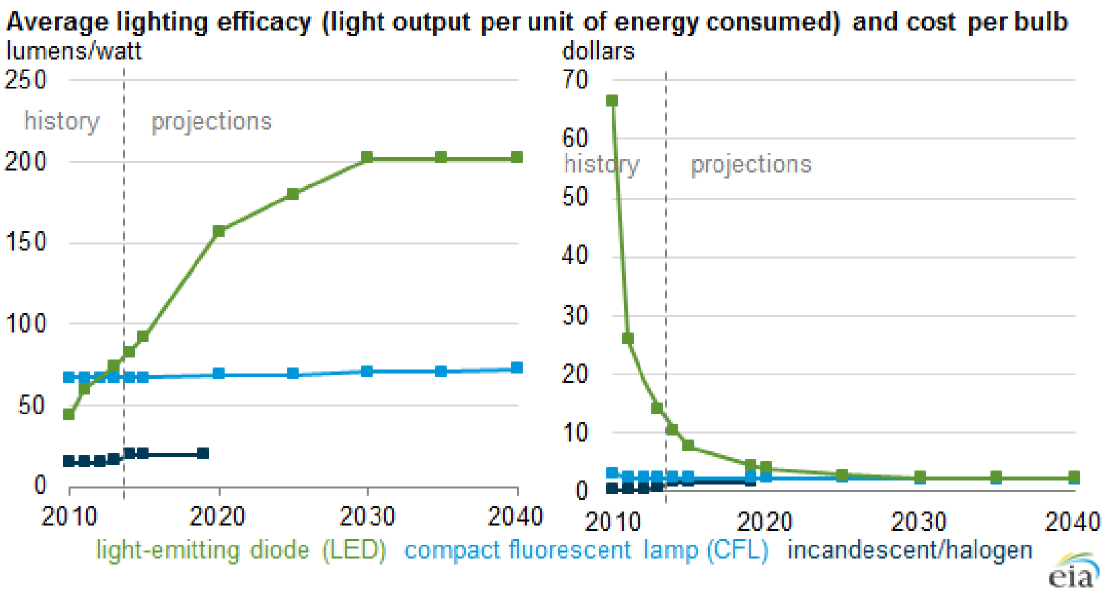

Figure 25: Average lighting efficacy and cost per bulb over the years (source: U.S. Energy Information Administration, Annual Energy Outlook 2014 Early Release)

[22] http://luxreview.com/article/2015/07/7-graphs-that-tell-you-everything-you-need-to-know-about-lighting

5.1.3 Wiring the wireless office

Until very recently every office desk space was equipped with a telephone line, a (Ethernet) network socket, one or more power sockets and lighting. Today many employees use wireless solutions for voice communication and connecting laptops and tablets to intranet and internet. However this requires wiring to more and more access points, because only smaller cells can facilitate the growing demand for higher data rates over wireless connections. Also the growing use of sensors, camera's, projectors, etc. often leads to more cabling instead of less. Additionally in larger buildings sometimes distributed antenna system or Distributed Antenna Systems (DAS) and femtocells of mobile operators also require cabling.

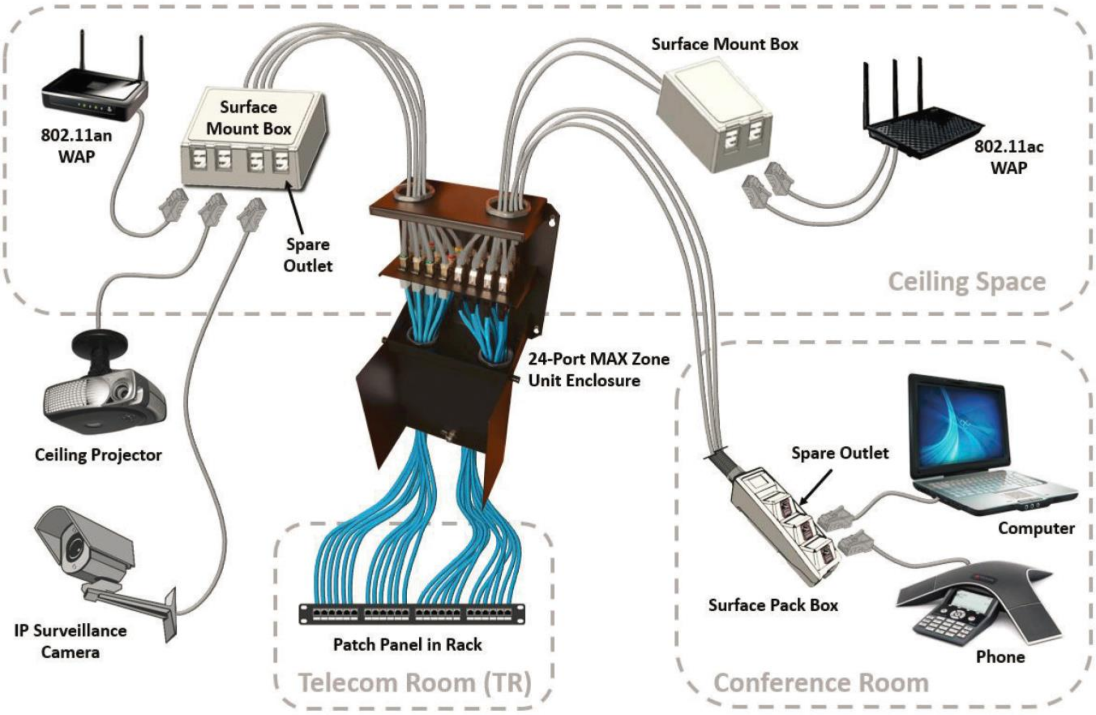

Figure 26: Example of Power over Ethernet based Zone Cabling Deployment Configuration (source: Siemon)

5.1.4 Power distribution is shifting towards low voltage DC power

As described in the previous section, lighting is becoming more energy efficient and connectivity is more important. LED Lighting solutions and also user equipment generally use low voltage direct current (DC). Traditional 230V power distribution requires many AC adapters to transform 230V AC to for instance 12V DC. Low voltage DC power distribution in buildings seems a good idea, however 230V is in most cases still needed for some equipment such as servers, coffee machines and vacuum cleaners.

Because sensors and (Wifi) access points become more and more part of (office) ceiling infrastructure, companies such as Philips Lighting[23] and Siemon[24] offer solutions that use Power over

[23] http://www.lighting.philips.nl/systemen/connected-lighting/connected-office-lighting
[24] https://www.siemon.com/uk/company/press_releases/17-02-22-poe-guide.asp

Ethernet cabling to combine and simplify the power distribution and communication infrastructure to lighting and sensor solutions.

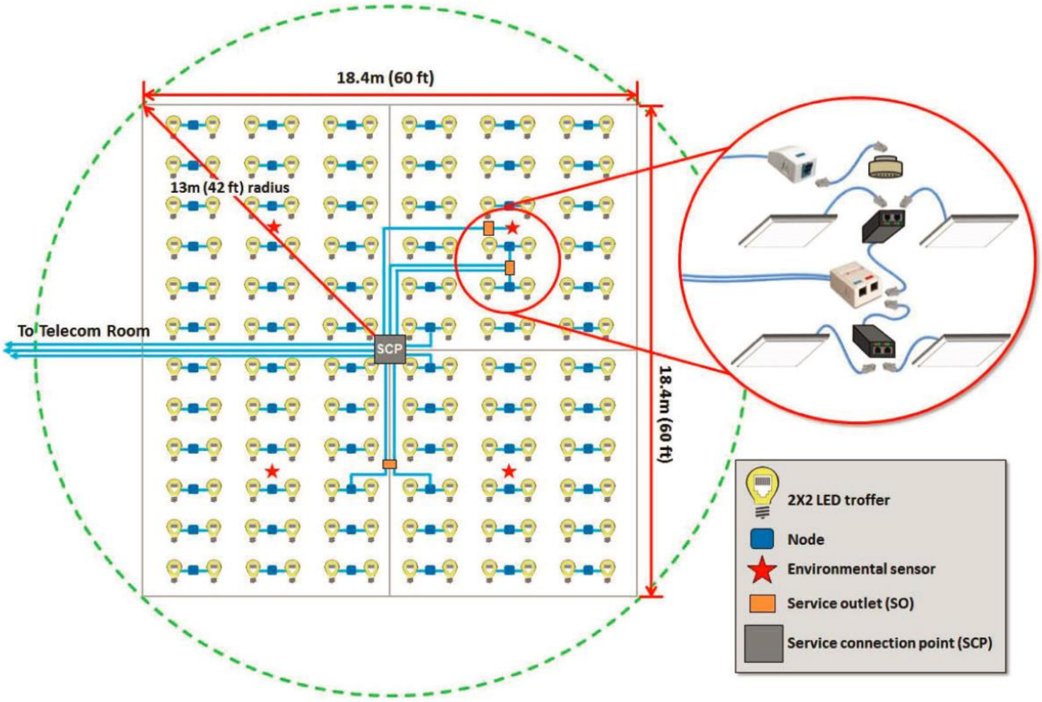

Figure 27: Example of coverage ceiling area with PoE based lighting design with environmental sensors. For simplicity, cabling is only shown to a sampling of nodes and one sensor (source: Siemon)

5.2 First products and first users

5.2.1 First OWC products on market

Recently the first OWC products for in-house use emerged on the market by various companies. Examples [54] are:

PureLifi is a start-up company founded in 2012 by Prof. Haas of the University of Edinburgh to market visual light communication technology after four years of extensive research. Currently there have been three releases:

- The Li-1th was introduced in 2013-2014 as the first LiFi technology available on the market. It provided a cost effective approach by using off the shelf LEDs. The system provided full duplex communication with a capacity of 11.5 Mbit/s [68]. It allows bidirectional communications and works from reflected surfaces as well as direct line-of-sight.
- The Li-Flame (2014-2015) is the second iteration that allowed mobile wireless communications. It made ubiquitous high-speed wireless networking using Lifi possible.
- The Lifi-X (2016-2017), was significantly smaller than its previous systems resulting in the first Lifi dongle. It was capable of providing a downlink and uplink speeds of 42 Mbit/s.

- Lifi-XC Access Point and Lifi-XC station (USB), currently offering high speed communications up to 43Mbit/s from each Lifi enabled LED light. In addition it is possible for Lifi-XC to be integrated into a device such as a laptop or tablet.

Lucibel is a French company specialising in new generation lighting solutions based on LED technology. Their solution, called Ores LiFi [69], deploys a wireless network using a bidirectional line with a data-rate of up to 42 Mbit/s. It supports multiple access of up to eight devices and it is capable of "handover". The handover functionality allows a stable connection between Ores Lifi devices [70].

SLUX is a Swiss company specialising in solutions that uses reflected signals, without the need for a direct Line of Sight (LOS). They have developed a Li-Bluetooth system using visible light for data transfer. It is capable of achieving 15 Mbit/s in duplex mode. In addition the company also developed light–transmitting wireless headphones [71].

LUCIOM is a French start-up company with two technologies based on Lifi [72]:

- Lifi tag (Geo VLC), which uses LED lighting to extract localisation information from the lights in the vicinity. There are in- and outdoor systems available.
- Broadband Lifi, which uses LEDs as Internet transmitters for high data rate solutions and it uses Lifi/infrared USB dongles to send and receive data. It has a downlink of 20 Mbit/s and an uplink of 5 Mbit/s [70].

Luciom has been taken over by Philips at the end of 2016 [73].

Basic6 is an American start-up company that specialises in light-based indoor positioning (GeoLifi) and communication. The system uses a store's or building's lighting infrastructure to anonymously deliver information to the customers and employees (e.g., proximity messaging, product information, promotion). In addition it is capable of producing detailed analytics like engagement rates between customer and employee or the department dwell times [74].

Velmenni is an Estonian start-up company. They developed a prototype consisting of a LED transceiver and an external photodetector receiver, which is connected to a device through USB. The system has data rate of up to 1 Gbit/s in duplex, with a distance of several tens of cm. The system has had successful trials in offices and industrial environment in the Talling, Estonia. In addition there have been numerous pilot projects using VLC in diverse industrial contexts [75].

Fraunhofer Heinrich Hertz Institute (HHI)'s Lifi Hotspot allows a high-speed network without the need for cables. The system is capable of providing bidirectional full-duplex data exchange up to 1 Gbit/s over a distance of 30 meter and it is easily aligned and inexpensive to install [9]. A prototype has been installed in a conference room on Mainau island, Germany[25]. HHI also provides components for Visible Light Communication with off-the-shelf white light LEDs using three light colors (RGB), capable of speeds of up to 3 Gbit/s.

Fraunhofer IPMS also offers the possibility for bidirectional full duplex communication up to 1Gbit/s and 30 meters reach[26].

[25] https://www.hhi.fraunhofer.de/en/press-media/news/news-archive/2015/fraunhofer-hhi-provides-vlc-technology-for-a-conference-room-on-mainau-island.html
[26] https://www.ipms.fraunhofer.de/de/research-development/wireless-microsystems/LiFi/lifi-hotspot.html

LVX System is an American company with a patented high quality LED light system capable of secured high-speed data stream. The company has signed a Space Act Agreement with NASA [76].

In addition to these products and the research behind the optical wireless communication variants described in paragraph 2.2 a wide range of research institutes and technical universities is involved in research projects regarding OWC or VLC, performing basic research on concepts and technologies, devising prototypes or proof of concepts and suggesting protocols or standards [77].

5.2.2 OWC solutions attract attention from user groups

Currently the first wave of Optical Wireless Communication products focus on markets that acknowledge the security and safety aspects of OWC. An interviewed manufacturer claimed that current customers include are army and defense industry, government and security organisations. Target markets include also hospitals, nurseries, schools and other public buildings. This is especially the case in France where a law[27] was passed in 2015 that bans the use of Wifi in nurseries and discourages Wifi in elementary schools

Although there is no substantial scientific evidence[28] that the use of Wifi or mobile equipment within the ICNIRP limits[29] can cause health risks, some users and user groups are worried about potential long term effects. Optical wireless communication solutions attract attention from those user groups as a potential communication solution for situations where Wifi solutions are not wanted or allowed, due to national legislation (such as in France[30] and Russia[31]) or due to local regulations and other actions[32] by pressure groups that believe that Wifi or mobile equipment are a potential health risk.

In the Netherlands a partnership between the branch organisation of the Dutch building services engineering sector UNETO-VNI and Eindhoven University of Technology is currently bringing together interested customers, service engineering companies and researchers to investigate the possibility of a pilot or proof of concept of OWC, together with other functionality such as better lighting and air quality, in schools[33].

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[27] http://www.powerwatch.org.uk/news/2015-02-05-france-wifi-restrictions.asp
[28] https://www.antennebureau.nl/onderwerpen/gezondheid-veiligheid/effecten-van-antennes-op-de-gezondheid
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[31] https://www.scribd.com/document/182641315/RNCNIRP-Russia-Wi-Fi-Regulation-19-06-12-pdf
[32] http://www.parentsforsafetechnology.org/worldwide-countries-taking-action.html
[33] https://kieninnovatiemeesters.nl/projects/frisse-school-en-een-razendsnelle-data-omgeving/

5.3 The potential future roles of Optical Wireless Communication

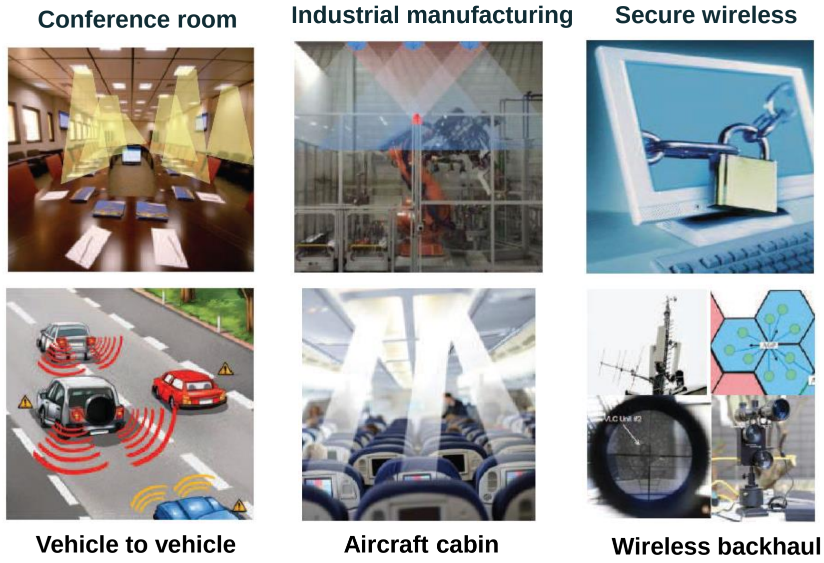

Figure 28: Some use cases for OWC (source: V. Jungnickel et al, "A European View on the Next Generation Optical Wireless Communication Standard," Proc. IEEE Conf. on Standards for Communications and Networking (CSCN), Tokyo, 28 - 30 Oct. 2015, pp. 106-110)

OWC is not hampered by electro-magnetic interference nor does it generate interference for EM-sensitive devices, it is nearly impossible to jam and offers a high level of privacy (e.g., does not penetrate walls), its installation can be relatively easy, and it gives access to a huge license-free spectrum. Building on its ability to selectively cover small areas, by means of spatial reuse it can offer a large aggregated capacity.

These characteristics are advantageous in densely-populated environments where people generate high traffic loads, such as in open office rooms, conference halls, exhibition halls, airplane cabins, train cabins, (virtual reality) gaming halls, etc. Its relative ease of installation (e.g., VLC may be integrated with lighting) and high privacy level makes it attractive for residential services at home.

Its EMI-insensitivity enables robust highly-reliable communication such as needed for industrial manufacturing robots, intra-data center top-of-the-rack interconnects, temporary (disaster-recovery) networks, etc.

Atmospheric conditions may hamper its use for outdoors, in particular over longer reaches and in foggy conditions. Mobile backhauling for small radio cells (spaced several hundreds of meters), car-to-car and car-to-roadside communication are examples of attractive outdoor scenarios.

As OWC needs line-of-sight, unlike Wifi, it cannot penetrate through walls nor through clothing. OWC therefore should not be considered as replacing Wifi fully. Its main benefit potentially is to offload high data rate traffic from the Wifi spectrum, thus remedying Wifi's congestion issues and taking care that Wifi gets ample room for its main strengths, to connect many non-LoS devices at low/moderate data rates (such as traffic expected in the upcoming internet-of-things).

The main indoor use foreseen is the delivery of high-capacity services, such as high-definition video streams, fast transfer of large data files, in a location-flexible way which excludes wire-bound connectivity.

OWC is already used in **small niche markets** and will be most probably implemented more niche markets where it has a definitive (safety) advantage and costs issues are relatively unimportant, such as the petrochemical industry and some manufacturing environments. As spectrum becomes more scarce OWC will be a more and more interesting solution for niche markets where many high bandwidth demanding users share a limited space, such as aircraft cabins, conference halls and stadiums,

When the number of niche markets and number of users grows, it may become an interesting solution for larger markets such as **indoor business use**. High end business device manufacturers may consider offering it as a standard component in their devices. This may lead the way to OWC technology becoming a **commodity**.

6 Conclusions and recommendations

In section 6.1 the conclusions of this research are summarised. In section 6.2 a number of recommendations are given.

6.1 Conclusions

There are several Optical Wireless Communication technologies that offer a promising solution for indoor wireless broadband communication over a distance up to a few meters. Potentially OWC is suitable for very high bandwidth communication over these distances.

OWC technologies are maturing and may help relieve spectrum scarcity

For communication using light, the spectrum of interest is 400-2000 nm. This wavelength spectrum corresponds to 150-750 THz carrier wave frequencies. The current radio spectrum operates at much lower carrier frequencies. One of the most important characteristics of THz frequencies is that the waves cannot penetrate solid materials. It will experience considerable attenuation once it finds obstacles in its path. Hence, communication in the THz frequency region needs a line-of-sight connection.

Another characteristic that is common for extremely high frequencies (EHF), which is a consequence of Frii's equation, is that the antenna gain at the transmitter and receiver side needs to be large. This is necessary in order to create a sufficient link budget for a good reception; hence the antenna's aperture is small, in addition the antenna needs to be well directed.

As OWC readily can be used to cover distinct areas in a cell-based network architecture, it enables the ultimate reuse of spectrum, for instance reusing the available spectrum per room or light source using very narrow infrared beams. Current and emerging OWC solutions can provide connections of medium to very high bandwidths (dependent on the solution) and very low latencies. It can therefore be used for a wide range of applications in environments, where devices do not require a high degree of mobility and where the line of sight between sender and receiver is not blocked. OWC will never be a complete substitution for radio technologies, especially in situations where a line of sight is not always possible (e.g., to mobile devices carried inside clothing), or is likely to be blocked.

Situations where OWC solutions already may have clear advantages are in the petrochemical industry (explosion hazards), or in manufacturing environments (robot welding), where radio communication or even wired communication is prohibited or can be susceptible to disturbances due to extreme influences. Principally, OWC can be used in a wide range of applications in a relatively stable (non-mobile) situation in offices, homes and factory environments, where it can potentially co-exist with existing and emerging radio technologies like Wifi. Whether and when OWC will become a commodity depends on several factors, such as the necessity (growth of data use), growth of the capability of end user devices such as laptops, tablets and phones to process higher data rates, availability of feasible alternatives (evolution of Wifi and 5G networks), the production costs, the establishment and evolution of OWC standards, and the interoperability features supported by the OWC solutions.

Also other elements in the communication chain between user and content may form potential bottlenecks that may influence the potential usability and uptake speed of OWC solutions.

To benefit from the full potential of OWC a high speed access network is required

For the last meters to the user, OWC techniques can offer a secure, robust and ultrafast connectivity to wireless terminals, hence these techniques can offload the bandwidth-hungry applications running on the current WiFi or future 5G technologies. Because of this, it is possible to free-up the spectrum capacity needed for dense communications that are less bandwidth-demanding (e.g., needed for the (upcoming) internet-of-things).

Since OWC can realise ultra-high speed links to wireless terminals, the underlying access infrastructure needs to be able to handle these high speeds. OWC is meant to complement wireless communication for pico-/femto-cell networks or other wireless solutions. Communication using radiospectrum will always be the major option in situations where mobility is more important. The main infrastructures and backbones of all fixed and wireless communication systems largely consist of fixed optical networks. Even most mobile antenna sites are connected by fiber. Only for short distances (the 'last mile'), the edge / last mile to homes and business premises , copper (twisted and coax) cables are still commonly applied. The full potential of OWC solutions can only be used if the access network is capable to process high data rates.

In-building fixed (wired) backhaul: an essential link in an OWC solution.

The indoor infrastructure that forms the bridge between access and the OWC solution needs to have a backbone network that can handle the high speeds that OWC can realise. This implies that we need to build communication highways between a central point (for example the utility meter cabinet) and light antennas (supporting the OWC) in all rooms. In businesses currently Ethernet cabling is used for data distribution. There is an emerging trend towards the use of Power over Ethernet for connecting both lighting and other low power equipment such as access points and sensors. In homes also Ethernet or Power over Ethernet can be used, or in some cases Powerline Communication (PLC) is a feasible option for lower data rates. This also relates to the trend towards more energy efficient and more intelligent LED lighting solutions in buildings.

However Ethernet has a limited scalability (currently up to ~ 1 Gbit/s per connection). When demand for high capacity data communication grows, it may become necessary to use an optical fiber infrastructure also for the in-building backhaul network. In addition to desired speeds, operational expenses such as energy bills need to be taken into consideration in finding the optimal solution. Also the potential for future network upgrading needs to be considered; optical fiber is 'future-robust', it offers plenty of headroom for capacity upgrades. Furthermore, outdoor access networks should be able to handle the data speeds coming from homes, offices, and public spaces. Current fiber access technologies based on passive optical networks should be expanded to include both the time and wavelength domain following ITU T's or IEEE's Next Generation PON standards.

Legal and regulative issues are still a relative greenfield.

At the moment there is no regulation for light and near light spectrum, as there is for radio spectrum, such as the EMC Directive 2014/30/EU that limits radiation of equipment to reduce interference with other equipment. OWC is an emerging technology. Some companies are starting to offer commercial products for VLC/Lifi. Till today, there is no major ongoing standardisation effort in this area, but IEEE has started to get interested in this field by having an IEEE 802.15 Task Group 7R1 on OWC technologies formed in 2015. This includes optical camera communication, LED identification, and Lifi. OWC protocols may benefit from reusing and interworking with existing standards, for instance with regard to discovery, registration, authentication, session setup, data encryption and security, and handover and roaming. For Lifi an effort has been started to reuse parts of the Wifi Suite (IEEE 802.11). Other options include reusing part of ITU-T G.hn, which could ease the interworking with in-building Power Line Communication (PLC) solutions.

OWC is relatively safe, but there are some points of attention.

The effect of light or infrared radiation on the human body depends on its wavelength, power density, and exposure time. The most critical human organ is the eye. OWC solutions in the Netherlands should be compliant with safety regulations such as NEN-EN-IEC 62471 (photobiological safety of lamps and lamp systems) and NEN-EN-IEC 62031:2008/A2:2015 (LED modules for general lighting - Safety specifications) and regulations for electrical installations. Besides intensity of light emitting sources these regulations also apply to for instance ensuring that it is clear whether equipment is switched on (to minimise electric shock risk). OWC solutions including the necessary communication backhaul and power supply for OWC access points need to be safe to install, inspect and maintain.

Also OWC solutions deploying infrared laser beams should conform to eye safety standards such as the ANSI Z-136 series and IEC 60825-1 series. Necessary backhaul and power supply for access points need to comply with NEN 1010 (Electrical installations for low-voltage - Dutch implementation of the HD-IEC 60364-series) and NEN 3140 (Operation of electrical installations - Low voltage).

Whether and when OWC will be successful also depends on economies of scale.

OWC can provide a very efficient way to offer wireless ultra-high bandwidth communication over short distances, without impact on radio spectrum. In principle, optical solutions may provide a more energy efficient and therefore cheaper alternative for communication than a combination of electrical wired and radio wireless communication. However the business case of OWC solutions highly depends on economies of scale and the application domain. For certain niche markets where radio spectrum is becoming scarce or the use of radio frequencies is complicated or discouraged, OWC solutions already become more and more interesting but product adoption is still in the ‘innovators’ phase.

6.2 Recommendations

We have seen the trend in the communication networks evolving from large cell sizes (macro-cells) offering low capacities (Mbit/s) to small cell sizes (pico/femtocells) offering large capacities (Gbit/s). This trend opens possibilities for technological ecosystems to compete and/or complement each other according to use cases.

1. Optical wireless has been evaluated in lab environments successfully. We recommend to ***start one or more pilot projects where VLC/Lifi and BS-ILC are tested in practical situations***. VLC/Lifi products start to be offered on the market or are already at high technology readiness level (TRL). It is recommended to start pilot projects using VLC/Lifi products. IR-OWC is currently at low TRL and with some additional engineering steps is getting close to the prototype level.

2. It is also recommended to ***stimulate close contacts between (national) industrial R&D and academic research***, as there is (still) much diversity in the OWC technologies being explored. Early identification of which are potential winning technologies among them and facilitating and promoting convergence and interworking will support the industrial development and speed up market introduction.

3. OWC is not replacing, but is complementing the use of other transmission as eg Wifi for in-building communication infrastructures in which OWC can off-load the bandwidth-hungry applications from Wifi. Due to this co-existence with the current Wifi technology, we recommend ***designing and building offices, public spaces and houses such that the potential of OWC is taken into account,*** *especially for creating the fixed (wired) infrastructure accommodating sufficient OWC access points and backhaul****.*** Combining transporting data with powering optical wireless Access Points using Ethernet cables (Power over Ethernet) becomes increasingly interesting, and therefore it is recommended to pay attention to it for construction purposes.

4. For optical wireless, eye- and skin-safety are the most critical issues. Skin-safety has a much higher optical intensity threshold than eye-safety. Although the use of optical wireless by the general public can be made safe for almost all conditions, we recommend to ***take a closer look to safety issues for people who are working in a close proximity of intense light sources for installation and maintenance.***

5. Optical wireless is an emerging communication and ranging technology. There are still challenges to overcome before being deployed commercially. We recommend to ***focus more on standardisation efforts by ITU or IEEE rather than governmental rules and limit governmental regulation primarily to limits with regard to health hazards, carbon footprint, and commercial competition.*** Standardisation will increase not only compatibility among industrial products but also compatibility with already deployed technologies.

6. The deployment of Optical Wireless Communication may be particularly interesting in environments where many high bandwidth demanding users access the network within a confined space, or where conventional radio technologies cannot be used, or cannot provide the necessary service level. ***Bringing together representatives from potential user groups, construction industry, communication industry, device manufacturers and solution providers*** may help to further advance use cases and requirements for standards and further developments and to identify niche markets where the introduction of OWC will be most beneficial.

7. Acceptance and deployment of OWC will benefit from a clear vision on interworking with existing or emerging popular wireless standards, such as Wifi, for instance in the area of authentication, encryption and seamless roaming between Access Points. It is recommended to ***promote reuse of existing solutions where possible, for instance with regard to authentication and signal encryption.*** A possible example of this is the effort of the Lifi community to reuse relevant parts of the IEEE 802.11 suite. Such reuse may ease the development of interworking mechanisms (for instance handovers) between OWC and radio communication technologies. Also this way new developments with a still relatively small user base may benefit from technical evolutions, maintenance efforts and improvements of solutions with a large user base, for instance with regard to security and safety.

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Annex A ITU-R Question 238/1

QUESTION ITU-R 238/1

Characteristics for use of visible light for broadband communications (2015)

The ITU Radiocommunication Assembly,

considering

a) that technology development is an on-going process that also opens new ways for use of spectrum;

b) that the use of visible light for communications currently receives renewed attention;

c) that visible light communications operate in the unregulated part of the frequency spectrum and therefore do not require an allocation in the Radio Regulations;

d) that the topic of possibilities of broadband use via visible light requires further study within ITU;

e) that in certain areas, e.g. in the space radiocommunications, optical communications have already been studied;

f) that optical broadband needs to avoid human hazards,

decides that the following Questions should be studied

1 What are the distinctive characteristics and efficiency gains of the use of visible light for broadband communications in terms of their use of the spectrum?

2 What are the overall objectives and user needs for the development of broadband communication in the spectrum area of visible light?

3 What are the new applications associated with visible light used for broadband communications?

4 What are the technical and operational characteristics, taking into account *considering f)*, needed for the further development of visible light communications?

further decides

1 that the results of the above studies should be included in one or more Recommendation(s) and/or Report(s);

2 that the above studies should be completed by 2019.

Category: S2

Annex B Contacted parties

Parties that were contacted for information and discussion

- Nikola Serafimovski, PureLifi (interview)
  - Director Business Strategy at PureLiFi Ltd Edinburgh, United Kingdom,
  - Chair of the IEEE 802.11 Light Communications Study Group
  - secretary of the committee for the IEEE 802.15.7r1 OWC
- Musa Unmehopa, Philips Lighting (introduction and reference)
  - Senior Director Standards & Regulations, Philips Lighting
  - Vice Chairman of the Board of Directors of the ZigBee Alliance
- Gerard Lokhoff, Philips Lighting (interview)
  - Standardisation professional
- Frank Driessen, Arne Duwaer, ASML (introduction and reference)
  - Market Research – Strategy Office, ASML
- Harald Haas, University of Edinburgh (interview)
  - LiFi research
- Michel Wijbrands, UNETO-VNI (introduction and reference)
  - Vakspecialist techniek & markt
- KIEN (several contacts and participation KIEN technodag about opportunities for optical communication in schools)
- Amaury Villemain, Lucibel (interview)
  - Lifi products in France and Belgium
- Niels Leijten, Ammanu (short interview)
  - LED products and installation
- Ronald Gronsveld, Rofianda (short interview)
  - Lighting solutions in several niche areas including agriculture, NEN commissie verlichting
- René Proost, Siemon (short interview)
  - Network cabling solutions for offices, datacenters
- Experts Stratix
  - telecommunication, business strategy, regulations
- Experts Technical University Eindhoven
  - Research optical wired and wireless technologies, radio wireless technologies

Workshop participants:

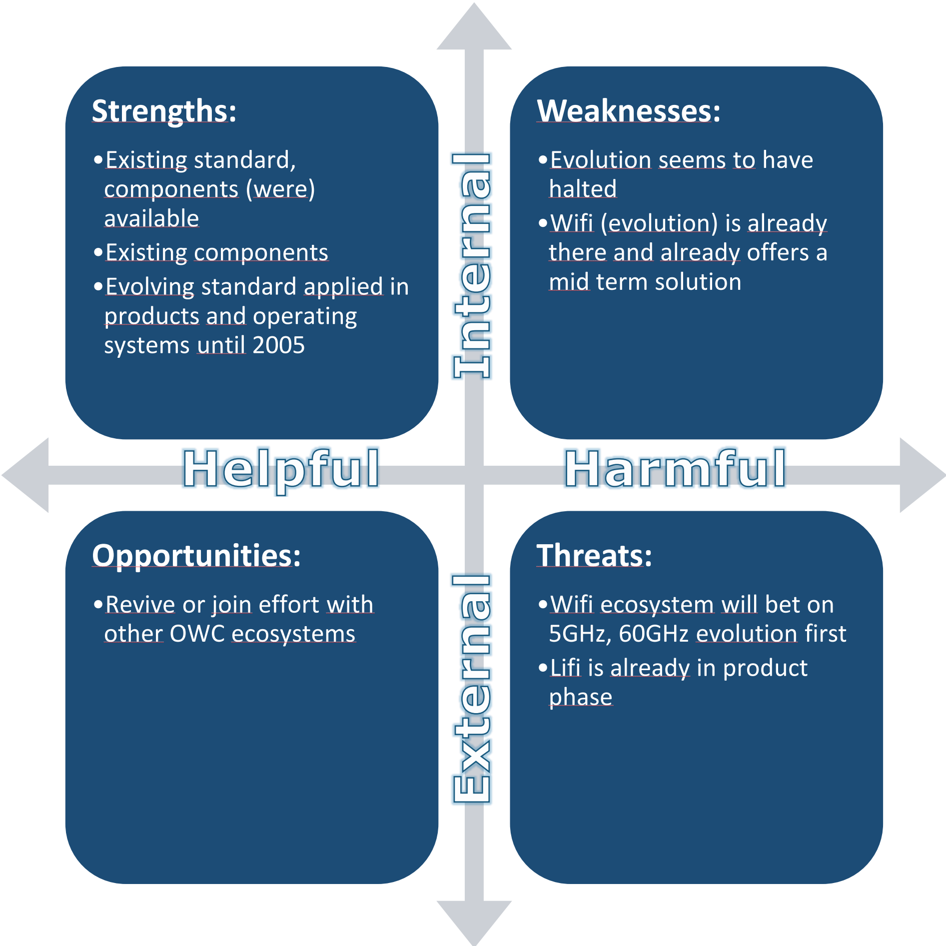
Name	Organisation
Ben Smith	Agentschap Telecom
René Vroom	Agentschap Telecom
Erik van Maanen	Agentschap Telecom
Jaap Steenge	Agentschap Telecom
Liesbeth Kruizinga	Agentschap Telecom
Pieter Mulder	Ammanu
Frank Driessen	ASML
Maurits Zandbergen	Flash/Ra
Herry den Besten	Kien Innovatiemeesters
Henk Hazeleger	Leertouwer BV
Gerard Lokhoff	Philips Lighting
Frans Panken	Surfnet
Nico Baken	TU Delft, KPN
Ignes Niemegeers	TU/e
Ton Koonen	TU/e
Manuel Janssen	Uitgekiend
Sietse van der Gaast	Stratix
Rudolf van der Berg	Stratix
Henny Xu	Stratix

Annex C SWOT matrices for OWC variants and alternatives

In addition to paragraph this annex an overview is given of the SWOT matrices that were a result of a short high level SWOT analysis of optical wireless communication variants and for communication technologies that are potential current or future alternatives for optical wireless communication technologies.

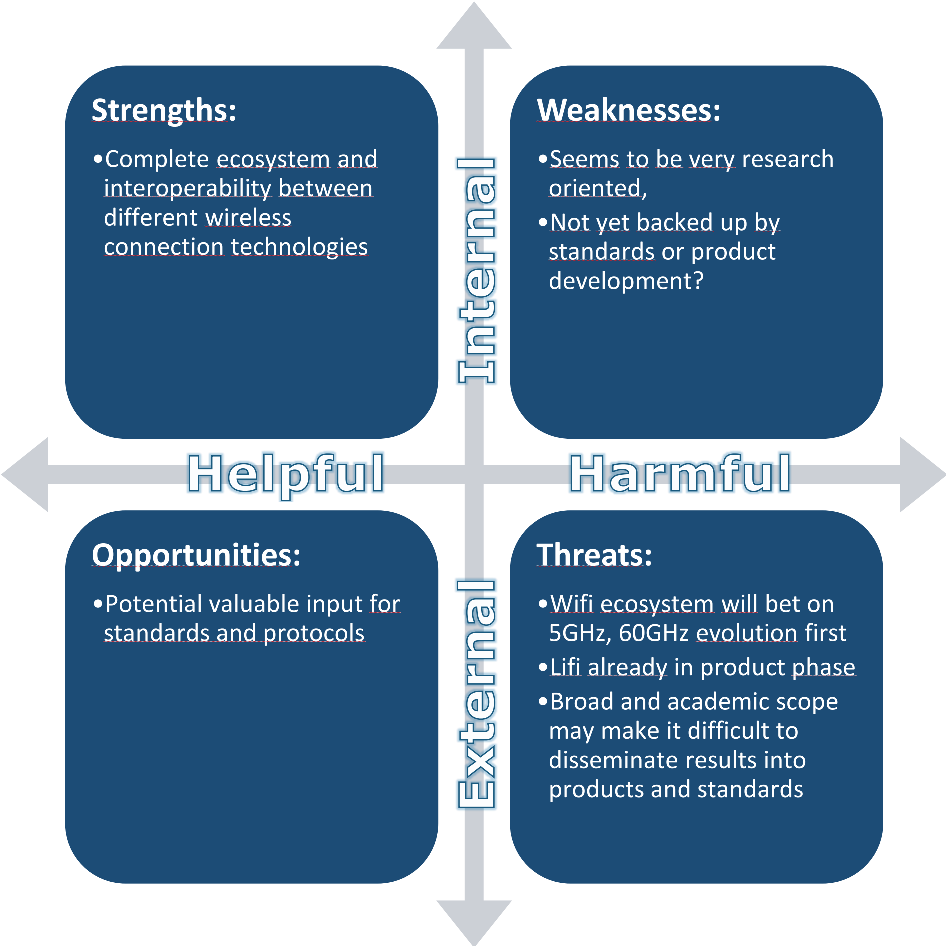
SWOT analysis matrices of additional OWC variants and initiatives

IrDA Infrared Data Association



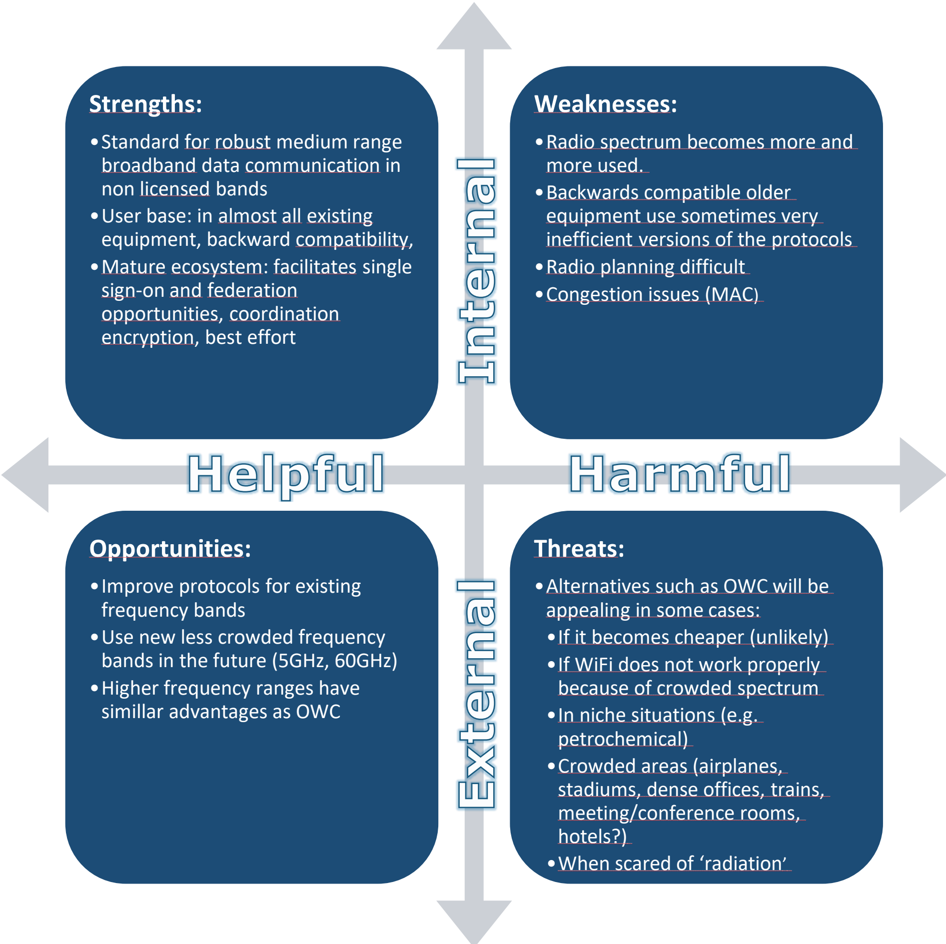
Optical Camera Communication (OCC)

IoRL 5G PPP: Internet of Radio Light 5th Generation Public Private Partnership

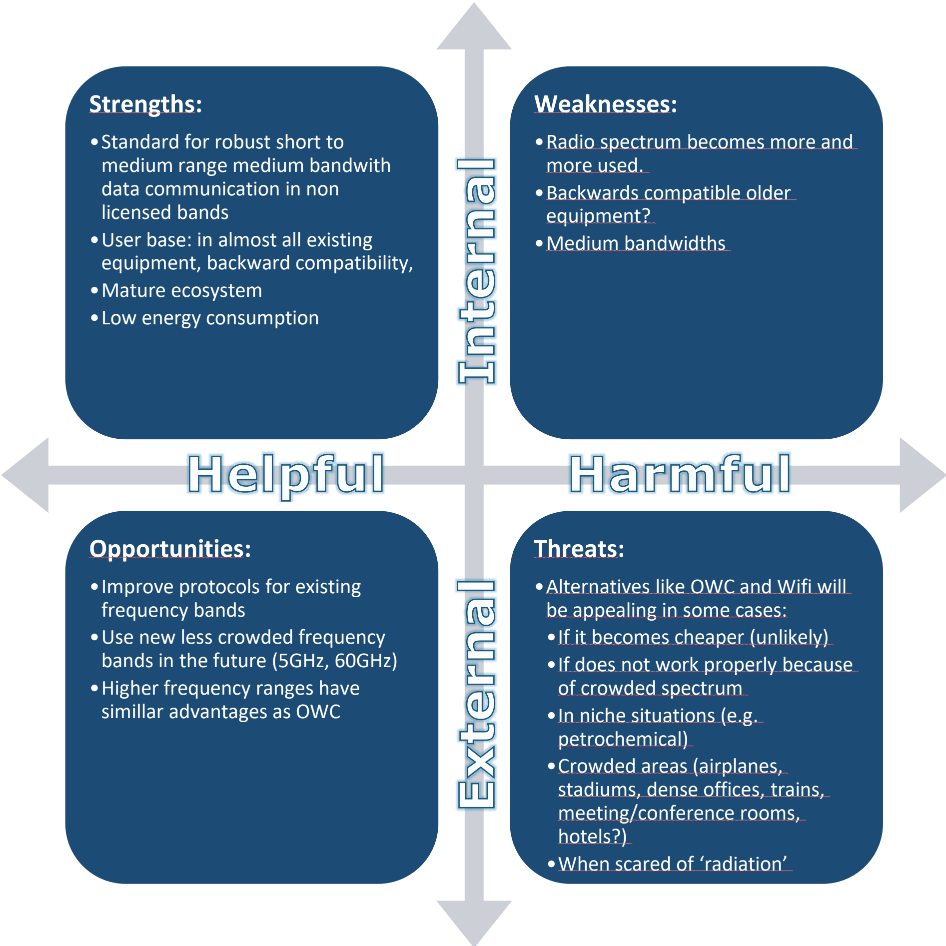


SWOT analysis matrices for OWC alternatives

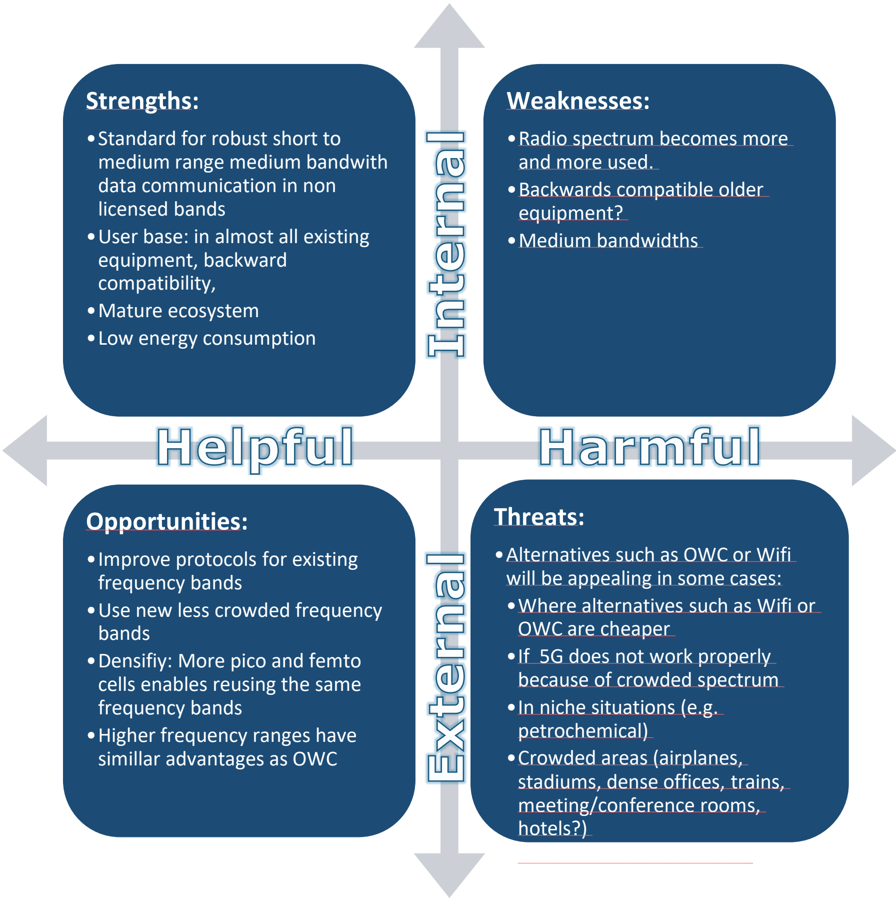
WiFi (IEEE 802.11)



Bluetooth (IEEE 802.15)

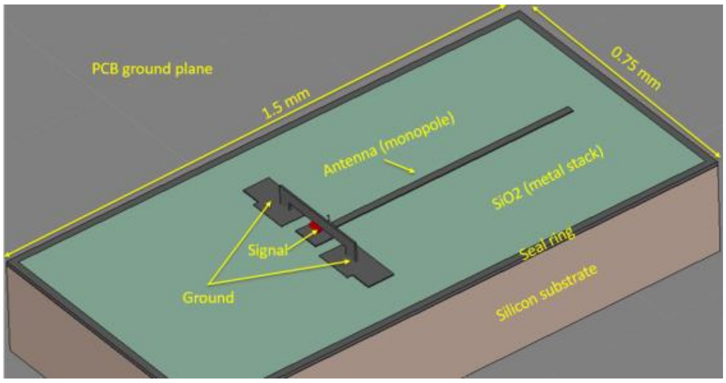


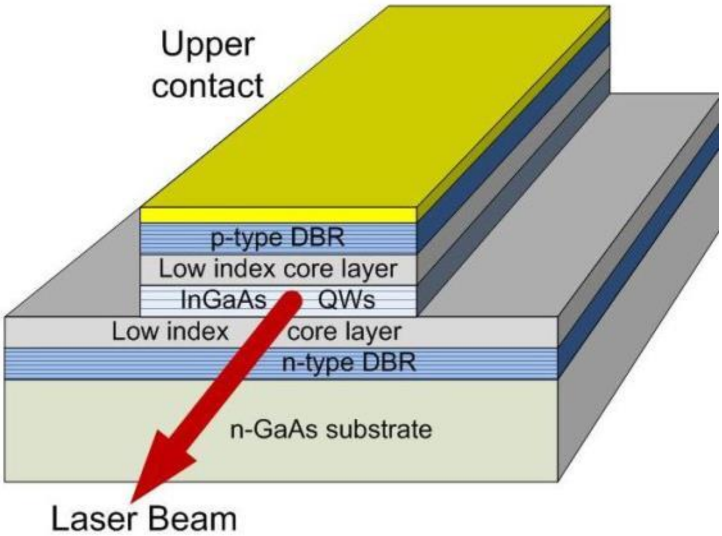
5G (3GPP, GSMA)


Strengths:
• Standard for robust short to medium range medium bandwith data communication in non licensed bands
• User base: in almost all existing equipment, backward compatibility,
• Mature ecosystem
• Low energy consumption
Weaknesses:
• Radio spectrum becomes more and more used.
• Backwards compatible older equipment?
• Medium bandwidths
Internal
Helpful
Harmful
External
Opportunities:
• Improve protocols for existing frequency bands
• Use new less crowded frequency bands
• Densifiy: More pico and femto cells enables reusing the same frequency bands
• Higher frequency ranges have simillar advantages as OWC
Threats:
• Alternatives such as OWC or Wifi will be appealing in some cases:
• Where alternatives such as Wifi or OWC are cheaper
• If 5G does not work properly because of crowded spectrum
• In niche situations (e.g. petrochemical)
• Crowded areas (airplanes, stadiums, dense offices, trains, meeting/conference rooms, hotels?)

Annex D Radio versus Light Antenna structures in silicon components

Radio antennas have a simple layer structure and they are usually made on a Silicon substrate. The antenna size is matched to the carrier frequency.





An optical source or laser has built on several layers of III-V In(GaAs)P materials which corresponds to a wavelength region of 1200-1700nm [80][81]. The size of a laser is much less than $1mm^3$. The active layer where light is generated is sandwiched by p- and n-type materials to ensure optical and electrical confinement. Because they are made from different structures and materials, light and radio antennas are difficult to be integrated together on the same substrate. Hybrid integration may be possible.

Annex E Considerations regarding eye safety

7.1.1 The human eye

As shown in Figure 8, the eye consists of several elements. Light enters the eye through the cornea, which is a thin transparent layer of tissue which protects the eye and for 70% is responsible for the refractive power. Next is the iris, a ring of muscle that controls the size of the eye's aperture, or pupil. Light passing the pupil enters the lens, of which the focus can be changed by circumferencing muscles. The light transmitted through the lens passes the inner volume of the eye which is filled with a viscous fluid (vitreous humour, or vitreous body). The light is focused in the back of the eye on the retina [78]. The retina is a layer of photosensitive cells and blood vessels. The actual centre of vision is an area of the retina where the photosensitive cells are largely concentrated; this area is called the macula lutea, and the most important part of it for our vision is the fovea centralis. When we want to see an object in detail we focus its image on this fovea. Close to the fovea, signals from the photosensitive cells are bundled in the optic nerve and leave the eye. These signals are processed by the human brain, and thus the function of visual perception is realised. The exit point of the optic nerve forms a small blind spot, as there are no photoreceptors there.

7.1.2 Safety risks of laser radiation

The eye may be injured by laser radiation in three ways:

- *Photothermally*. Some of the radiation is absorbed by tissue (cornea, lens, retina) and may yield a temperature rise. In the retina, the blood vessels may cool it down; however, at temperatures above 60 deg. Celsius degeneration of the tissue is caused. In the lens cataracts may be caused when proteins in the lens denature.
- *Photochemically*. This effect occurs at high photon energy, such as in ultraviolet (UV) light. The chemical structure of certain tissues may be changed. Such effects occur after a long time of exposure, and also recovery may occur.
- *Photoacoustically*. This effect may arise when high-energy pulses of short duration (<10μs) are used. Significant amounts of energy may be absorbed in such a small time scale that the fluid in a cell may evaporate fast. The energy thus may give an acoustic shock and may mechanically damage the cellular structures.

The *transparency of the various parts of the eye* is dependent on the wavelength, as illustrated in Figure 9. The eye is transparent between 400 and 1400 nm, so a light beam with such wavelength entering the cornea may be focused on the retina and absorbed there. The power density in a small area of the retina may become very high and cause damage through the photothermal effect. In the range 1400-3000 nm, light is absorbed in the lens and the cornea. At sufficiently high power levels and sufficiently long exposure time, this may cause cataract and opacity. Below 300 nm and beyond 3000 nm, the light is absorbed in the cornea (and partly in the thin tear film on the cornea). The upper layer may recover within 48 hours (cf. the arc-welding eye). Deeper layers may get scars, leading to loss of focus, bind spots or opacity.

The risk for eye damage can be expressed in the *maximum permissible exposure* (MPE), which is the highest power or energy density (in W/m^2 or J/m^2) of a light source that is considered safe, i.e. that has a negligible probability for creating damage [79][32]. It usually is about 10% of the dose which has a 50% chance of creating damage under worst-case conditions. The MPE is measured at the cornea or at the skin, for a given wavelength and exposure time. The most stringent limit for the MPE is the MPE measured at the cornea. The MPE at the cornea for the various wavelength regions and exposure time is laid down in Table 6 of the recommendation IEC 60825-1 [33], shown in Table 6 (from [79]).

7.1.3 Safety risk analysis for optical wireless communication with infrared beams

As outlined above, light at a wavelength in the 1.5μm region does not reach the retina, which is the most vulnerable part of the eye, but is stopped at the lens (see Figure 9). Figure 29 shows that the lowest MPE power density for this wavelength region is incurred at very long exposure times (10 to $3x10^4$ s), and is 1000 W/m^2. The infrared pencil beam diameter typically will be larger than 1 cm, which implies that the maximum permissible optical power of the beam is

$$P_{\max} = \frac{\pi}{4} D^2 \cdot MPE_{\min} \geq 78.5\, mW$$

which is far beyond the power levels envisaged. For larger beam diameters, the maximum permissible optical power rises quadratically with the beam diameter, as shown in Figure 29.

Hence, taking the international recommendation IEC 60825-1 into account, optical infrared pencil beams with a diameter beyond 1cm and power <10mW do not provide safety risks for the persons involved.

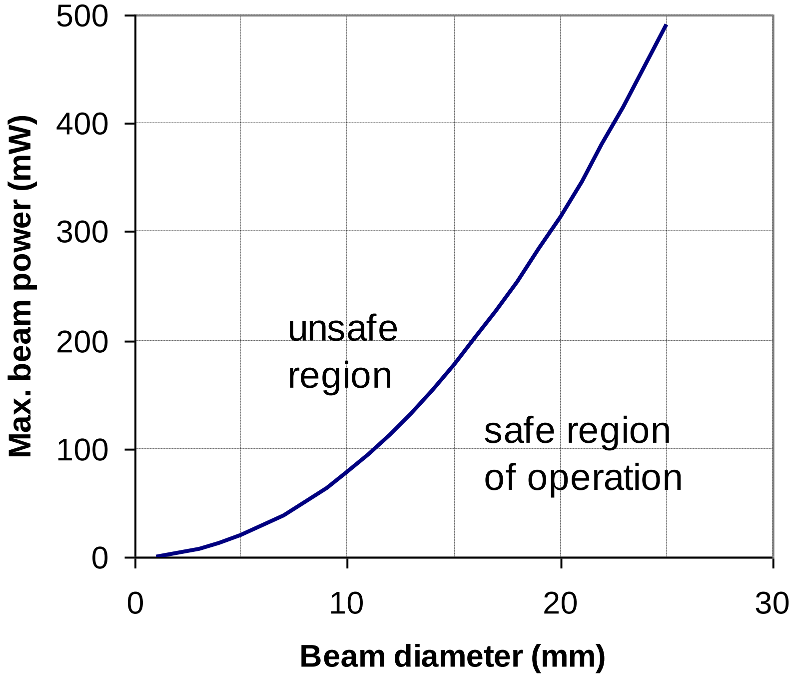


Figure 29: Maximum permissible beam power at 1.5μm wavelength versus beam diameter, for MPE=1000 W/m^2

Table 6: Table 6 of IEC 60825-1, MPE at the cornea for direct exposure to laser radiation [79]

Table 6 – Maximum permissible exposure (MPE) at the cornea for direct exposure to laser radiation [a, b, c]

<table>
<tr><th>Exposure time t in s / Wavelength λ in nm</th><th>10^{-13} to 10^{-11}</th><th>10^{-11} to 10^{-9}</th><th>10^{-9} to 10^{-7}</th><th>10^{-7} to $1,8 \times 10^{-5}$</th><th>$1,8 \times 10^{-5}$ to 5×10^{-5}</th><th>5×10^{-5} to 1×10^{-3}</th><th>1×10^{-3} to 10</th><th>10 to 10^2</th><th>10^2 to 10^3</th><th>10^3 to 10^4</th><th>10^4 to 3×10^4</th></tr>
<tr><td>180 to 302,5</td><td colspan="2" rowspan="3">3×10^{10} W·m^{-2}</td><td colspan="9">30 J·m^{-2}</td></tr>
<tr><td>302,5 to 315</td><td colspan="5">($t \leq T_1$)
C_1 J·m^{-2}
C_2 J·m^{-2}
($t > T_1$)</td><td colspan="4">C_2 J·m^{-2}</td></tr>
<tr><td>315 to 400</td><td colspan="5">C_1 J·m^{-2}</td><td colspan="2">10^4 J m^{-2}</td><td colspan="2">10 W m^{-2}</td></tr>
<tr><td>400 to 700[d]</td><td>$1,5 \times 10^{-4}$ C_6 J·m^{-2}</td><td>$2,7 \times 10^4$ $t^{0,75}$ C_6 J·m^{-2}</td><td colspan="2">5×10^{-3} C_6 J·m^{-2}</td><td colspan="3">18 $t^{0,75}$ C_6 J·m^{-2}
400 to 600 nm[d]
400 to 700 nm[d]</td><td colspan="4">400 to 600 nm[d]: Retinal photochemical hazard
10 to 10^2: 100 C_3 J·m^{-2} using γ_p = 11 mrad
10^2 to 10^4: 1 C_3 W·m^{-2} using γ_p = 1,1 $t^{0,5}$ mrad
10^4 to 3×10^4: 1 C_3 W·m^{-2} using γ_p = 110 mrad
AND[d]
400 to 700 nm[d]: Retinal thermal hazard
($t \leq T_2$) 18 $t^{0,75}$ C_6 J·m^{-2}
($t > T_2$) $\alpha \leq 1,5$ mrad: 10 W·m^{-2}
$\alpha > 1,5$ mrad: 18 C_6 $T_2^{-0,25}$ W·m^{-2}</td></tr>
<tr><td>700 to 1 050</td><td>$1,5 \times 10^{-4}$ C_4 C_6 J·m^{-2}</td><td>$2,7 \times 10^4$ $t^{0,75}$ C_4 C_6 J·m^{-2}</td><td colspan="2">5×10^{-3} C_4 C_6 J·m^{-2}</td><td colspan="3">18 $t^{0,75}$ C_4 C_6 J·m^{-2}</td><td colspan="4" rowspan="2">($t \leq T_2$)
18 $t^{0,75}$ C_4 C_6 C_7 J·m^{-2}
($t > T_2$)
$\alpha \leq 1,5$ mrad: 10 C_4 C_7 W·m^{-2}
$\alpha > 1,5$ mrad: 18 C_4 C_6 C_7 $T_2^{-0,25}$ W·m^{-2}</td></tr>
<tr><td>1 050 to 1 400</td><td>$1,5 \times 10^{-3}$ C_6 C_7 J·m^{-2}</td><td>$2,7 \times 10^5$ $t^{0,75}$ C_6 C_7 J·m^{-2}</td><td colspan="3">5×10^{-2} C_6 C_7 J·m^{-2}</td><td colspan="2">90 $t^{0,75}$ C_6 C_7 J·m^{-2}</td></tr>
<tr><td>1 400 to 1 500</td><td colspan="2">10^{12} W·m^{-2}</td><td colspan="4">10^3 J·m^{-2}</td><td>5 600 $t^{0,25}$ J·m^{-2}</td><td colspan="4" rowspan="4">1 000 W·m^{-2}</td></tr>
<tr><td>1 500 to 1 800</td><td colspan="2">10^{13} W·m^{-2}</td><td colspan="5">10^4 J·m^{-2}</td></tr>
<tr><td>1 800 to 2 600</td><td colspan="2">10^{12} W·m^{-2}</td><td colspan="4">10^3 J·m^{-2}</td><td>5 600 $t^{0,25}$ J·m^{-2}</td></tr>
<tr><td>2 600 to 10^6</td><td colspan="2">10^{11} W·m^{-2}</td><td>100 J·m^{-2}</td><td colspan="4">5 600 $t^{0,25}$ J·m^{-2}</td></tr>
</table>

[a] For correction factors and units, see "Notes to tables 1 to 4".

[b] The MPEs for exposure times below 10^{-9} s and for wavelengths less than 400 nm and greater than 1 400 nm have been derived by calculating the equivalent irradiance from the radiant exposure limits at 10^{-9} s. The MPEs for exposure times below 10^{-13} s are set to be equal to the equivalent irradiance values of the MPEs at 10^{-13} s.

[c] The angle γ_p is the limiting angle of acceptance for the measuring instrument.

[d] In the wavelength range between 400 nm and 600 nm, dual limits apply and the exposure must not exceed either limit applicable. Normally photochemical hazard limits only apply for exposure durations greater than 10 s; however, for wavelengths between 400 nm and 484 nm and for apparent source sizes between 1,5 mrad and 82 mrad, the dual photochemical hazard limit of 100 C_3 J m^{-2} shall be applied for exposures greater than or equal to 1 s.

CONTACT

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