Chapter 1
An Overview of Optical Wireless Communications

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Abstract We are continuously witnessing the emergence of new data services and applications in wireless transmission systems, in particular mobile broadband services, which require enhancing user's experience. The existing radio frequency based wireless communications are facing challenges in so far as being able to cope with these varied, sophisticated and bandwidth hungry services and applications. The ever evolving optical wireless communications (OWC) technology with its unique features such as a license-free frequency spectrum, an inherent security, and significantly higher transmission rates is seen as a potential alternative and complementary to the radio frequency based wireless communications, which can address some of these challenges. This technology can be used for short to long distance applications as in indoor visible light communications, ultra-violet, and free space optics. The chapter gives an overview of the OWC system focusing on the historical development and current status, as well as existing and envisioned applications areas.

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1.1 Introduction

In the past decade, the world has seen a growing increase in the traffic carried by the telecommunication networks including the wireless networks. The ever increasing demand for broadband internet services has underpinned the need for further innovation, research and development in the new emerging communication technologies capable of delivering ultra-high data rates. Wireless technologies are one of the greatest success stories in the history of technological development, realizing the dream of humans to communicate from anywhere at any time. While voice communications was the primary service some ten years ago, wireless data and mobile Internet have become pervasive much more rapidly than anyone could have imagined and augmented voice communications with much richer multimedia contents. Wireless devices, applications and services have already radically changed the way we live, work, and socialize. New bandwidth hungry applications being developed are creating a significant further demand for mobile data delivery. An additional three orders of magnitude more mobile data traffic is expected by 2020 as compared to 2010, while the spectrum for mobile services is to be approximately doubled [1]. This is also referred to as the mobile spectrum crunch, which is being addressed as part of the fifth generation (5G) wireless communication [2–4]. The emerging concept of Internet of things (IoT), which has been most closely associated with machine-to-machine (M2M) communication, further promises wireless connectivity among natural and human-made objects, sensors, etc. in the environment realizing ubiquitous machine-to-machine and machine-to-human communications. This would further change the way we interact with the physical world and make wireless communications an integrated part of the human life.

Today, the term "wireless" is widely used as a synonym of radio frequency (RF) technologies as a result of the worldwide domination of RF devices and systems. The RF band lies between 30 kHz and 300 GHz of the electromagnetic

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spectrum and its use is strictly regulated by the local and international authorities. In most cases, sub-bands are exclusively licensed to the operators, e.g., cellular phone operators, television broadcasters, point-to-point microwave links etc. The existing RF wireless spectrum is outstripping the supply, thus leading to the spectrum congestion (or bottleneck). Such situations arise in high density scenarios, where user demands may lead to the dramatic situation of limited access. Current RF based wireless communication systems (WCS) suffer from multi-path effects in dense urban environment, which deteriorate the link performance. The bandwidth of these systems together with spectrum congestion means that relatively very few high-definition channels can be accommodated in a given area. This problem is more equate at indoor applications where there is a lack of enough bandwidth to be shared among the large number of users. It is estimated that more than 70 % of the wireless traffic takes place in an indoor environment (home/office etc.). Therefore low-cost and highly reliable technologies are required to enable a seamless indoor WCS.

Squeezing more out of RF based technologies or using an alternative such as optical technologies are the only two options available. Regardless of the technologies (i.e., 3G, 4G, 5G or Wi-Fi) being adopted, there are only three approaches to increase the capacity of wireless radio systems: (i) release of a new spectrum and therefore more bandwidth, (ii) more nodes, (iii) elimination of the interference, and (iii) highly improved frequency reuse of the available frequency resources. Acquiring a new spectrum is very costly, and finding more bandwidth is not a major problem but it is clearly not enough—it is finite. Additional nodes can be included by means of cell splitting, which is rather costly. Also, two nodes do not offer twice the capacity of one, due to interference issues. In addition, doubling the infrastructure will not lead to doubling the revenue. Finally, the wireless technology spectral efficiency has improved over the years, but it is slowed to less than 20 % in recent years. So in the long run, what are the solutions?

One possible alternative complementary technology that can address and overcome these restrictions is the optical wireless communication (OWC), which offers practically an unlimited bandwidth (400 THz) and includes **infrared (IR)**, **visible (VL)** and **ultraviolet (UV)** sub-bands, as shown in Fig. 1.1. The use of these bands

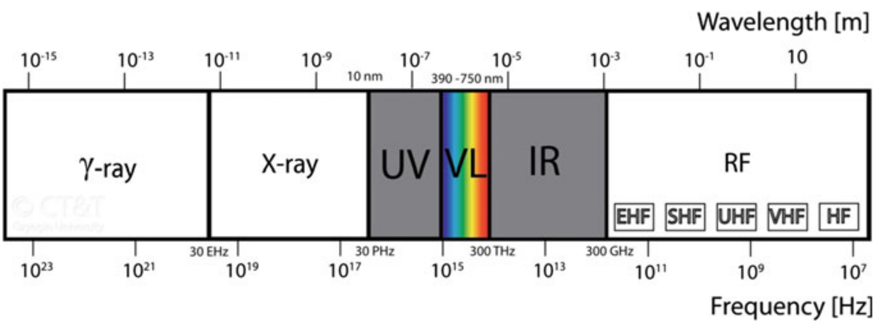

Fig. 1.1 The electromagnetic spectrum

for communications purposes offers unique opportunities, which remain mostly unexplored so far. In comparison to the RF counterparts, OWC [5, 6] enjoys superior features such as ultra-high bandwidth, robustness to electromagnetic interference, a high degree of spatial confinement bringing virtually unlimited frequency (or wavelength) reuse, and inherent physical security. Furthermore, since OWC technologies can be operated in the unregulated spectrum, no licensing fee is required thus leading to a cost-effective solution for a number of applications. For example, in an indoor environment a wireless link can greatly benefit from the high signal-to-noise ratio offered by the light emitting diodes (LED) based illumination room instead of using a high power RF based outdoor base station to provide services. Therefore, in such scenarios the logical approach would be to effectively utilize RF base stations to serve outdoor users in particular fast moving mobile users, and use the LED lighting for indoor slow moving mobile users. This approach offers four key features: (i) entirely avoiding the interference between the outdoor and indoor users, (ii) with no interference, lower power RF base station, thus 'greener' mobile networks, (iii) most effective utilization of the scarce wireless transmission resources, and (d) improved user experience and reduced costs.

In OWC systems modulation/demodulation is direct as there are no radios or antennae, therefore adding more nodes is straightforward as they do not introduce interfere as in RF based systems. With ample resources, spectral efficiency is less sensitive in OWC and what has been developed for RF spectral efficiency can be used. To use higher frequencies in RF based technologies to deliver the needed capacity requires path management, which makes the use of OWC in 'managed' situations more likely. The term OWC refers to any optical transmission in an unguided media although its variations based on the operating wavelength (frequency) might have different use as elaborated in the following. OWC systems operating in the visible band (390–750 nm) are commonly referred to as **visible light communication (VLC)**. VLC systems take advantage of both laser diodes and LEDs, which can be switched on and off at a very high speed without any noticeable effects on the lighting output and human eye. The multiple use of visible LEDs for illumination, data communication, and indoor localization purposes is a sustainable and energy-efficient approach and has the potential to revolutionize how we will use lights in the future. VLC for data communications can be used in a wide range of applications including wireless access point, wireless local area networks, wireless personal area networks and vehicular networks among others.

On the other hand, terrestrial point-to-point OWC systems, also known as the **free space optical (FSO) systems**, operate at the near IR frequencies [7]. These systems typically use laser transmitters and offer a cost-effective protocol-transparent link with high data rates, i.e., 10 Gbps per wavelength, and provide a potential solution for the backhaul bottleneck [8]. LED based FSO systems have been reported where data transmission rate by VLC is limited and strongly depends on the distance and atmospheric conditions. The transmission span depends on the irradiation angle of the visible light, the feature that is utilised for rough pointing. Without precise pointing between the transmitter and receiver, low bit rate free space data transmission using VLC has been achieved for satellite based combinations [9]. In outdoor applications, similar to the RF technology, FSO links face a number of challenges that will affect its wide usage. These challenges are related to the atmospheric conditions (fog, turbulence etc.) and building sway, which will affect the link availability at all times. However, these problems can be overcome by employing hybrid FSO and RF radio links. Despite being a predominantly an outdoor technology with several field applications, FSO can also be used in indoor environments (i.e., big organisations) to provide high bandwidth connectivity in multi-point scenarios. This represents a great solution to bridge the optical fiber connectivity with several points within large areas without the need for extensive infrastructure adaptation. In this sense, FSO may also provide the best solutions for fiber optic system replacement and deployment in modern building. It can also play a significant role in another growing research trend on radio-over-FSO with many similarities with the well-established radio-over-fibre systems.

There has also been a growing interest on **ultraviolet communication (UVC)** as a result of recent progress in solid state optical sources/detectors operating within solar-blind UV spectrum (200–280 nm). In this so-called deep UV band, solar radiation is negligible at the ground level and this makes possible the design of photon-counting detectors with wide field-of-view receivers that increase the received energy with little additional background noise. Such designs are particularly useful for outdoor non-line-of-sight configurations to support low power short-range UVC such as in wireless sensor and ad hoc networks [10].

1.2 Historical Overview and Current Status

Signalling through smoke, beacon fires, torches and sunlight can be considered the historical forms of OWC. The earliest use of light for communication purposes is attributed to ancient Greeks and Romans who used their polished shields to flash sunlight for delivering simple messages in battles [11]. In late nineteenth century, heliographs were used commonly for military communication. These devices involve a pair of mirrors to direct a controlled beam of light (typically sunlight during the day and some other form of bright light such as a Kerosene flame during night) to a distant station. Heliographs remained part of the signalling equipment in the tactical field until early twentieth century. Another historical milestone in the area of OWC is the photophone invented by Alexander Graham Bell. In 1880, Bell was able to transmit voice signals using optical signalling at a distance of some 200 m. His simple experimental set-up was based on the voice-caused vibrations on a mirror at the transmitter. The vibrations were reflected and projected by sunlight and transformed back into voice at the receiver. This was made possible using a photoconductive selenium cell connected to a pile and ear-phones. Photophone never came out as a commercial product, but the military interest on photophone continued and high pressure arc lamps were used as light sources to establish voice communication links in the tactical field.

During the following century, RF and fiber-optic communications developed very fast and dominated the global telecommunication market. Nevertheless, several early FSO experiments of historical interest, recorded in the early 1960s into 1970s, are worth to mention [12]. In July 1960, just months after the first public announcement of the working 632.8 nm Helium-Neon (He–Ne) laser, Bell Labs were able to transmit signals 40 km away using a ruby laser [13]. In November 1962, Hughes Research Labs used a He–Ne laser excited by an HF amateur radio transmitter and sent voice signals over a distance of 30 km. A photomultiplier was used to detect the light signal of intensity modulation, and a high-pass filter was employed to reduce the effects of the optical scintillation. In May 1963, a similar transmission link using a voice-modulated He–Ne laser beam was established from Panamint Ridge to San Gabriel Mountain by Electro-Optics Systems, where the link distance was extended to 190 km. The TV-over-laser transmissions with the modulation bandwidths of 1.7 and 5 MHz were achieved by North American Aviation and Hughes in 1963, respectively. A full duplex 632.8 nm He–Ne laser communication link over a total distance of 14 km, built in Japan by Nippon Electric Company around 1970, was the first FSO link to handle a commercial traffic. A comprehensive list of OWC experimental demonstrations during 1960–1970 is reported in [13]. However, the results were in general disappointing due to large divergence of laser beams and the inability to cope with atmospheric effects. With the development of fiber optics in the 1970s, they became the obvious choice for long distance optical transmission and shifted the focus away from OWC systems. Nevertheless, their development was never stopped in military applications [14] and in space application laboratories, mainly European Space Agency (ESA) and National Aeronautics and Space Administration (NASA). For instance, near-Earth "lasercom" systems were demonstrated under the programs of Geosynchronous Lightweight Technology Experiment (GeoLITE) and Global-scale Observations of the Limb and Disk (GOLD) in USA, and Semiconductor Inter-satellite Link Experiment (SILEX) in Europe. The Mars Laser Communications Demonstration (MLCD) Project was a Mars mission that was originally intended to launch by NASA in 2009 and would have established an interplanetary laser communication link between Earth and Mars with the aim of achieving a high transmission rate of up to 10 Mbps. The Lunar Laser Communications Demonstration (LLCD) project, sponsored by NASA, aims at demonstrating the world's first free-space laser communication system that can operate over a range of about 400,000 km that is ten times larger than the near-Earth ranges that have been demonstrated to date. It demonstrated high-rate (up to 622 Mbps) laser communication from a lunar orbit to a terminal on Earth.

In parallel with space-application researches and with the progresses made in the fabrication technology of optical transmission and detection components, OWC also received increasing attention in military applications due mainly to its high inherent security. OWC's mass market penetration has remained limited with the exception of IrDA [15] which became a highly successful wireless short-range transmission solution in 1990s and some success of FSO links particularly as a redundant link where fiber optic installations were not possible or feasible. In the

1990s, a considerable interest for the civilian use of FSO appeared, which was driven by the growing demand for higher data rates and higher-quality connectivity from commercial customers. In particular, FSO can help service providers reach the customers' demand without the prohibitive costs of deploying fiber. This market of FSO spawned many manufacturing companies, e.g., Lightpointe, MRV, CableFree, and MOSTCOM, and a great deal of the commercial FSO systems have been designed and manufactured. Some of them allow transmission with data rates of up to several Gbps and link spans of up to several kilometers. In 2012, the global market for devices used in commercial FSO communication systems grew by 13 % on the previous year, reaching of $30 million. Current forecasts expect that the market for commercial FSO systems will nearly double by 2018 [16].

In the last decade, there have also been significant research efforts to improve the FSO system performance in the presence of atmospheric turbulence and adverse weather effects, see [17] and the references therein. FSO products with transmission rates of 10 Gbps are already in the market and the speeds of recent experimental FSO systems are competing with fiber optic [18, 19]. It is expected that such high-performance FSO systems can be used in the backhaul as an integral part of next generation heterogeneous wireless networks to provide a seamless connection with fiber optic counterparts.

In recent years, particularly with the emergence of VLC in providing illumination, data communications, and indoor localization, the OWC market has begun to show future promise [20–22]. The emergence of VLC is in fact a result of recent development in solid state lighting technologies. New generations of solid state silicon LEDs have attractive features such as a long life expectancy, high tolerance to humidity, lower power consumption and reduced heat dissipation. Incandescent bulbs and fluorescent lights are gradually replaced with such energy-efficient lighting technologies; therefore, it is predicted that LEDs will be the ultimate light source in the near future. In 2000, KEIO research group in Japan outlined the first concept that white LEDs can be used for wireless home link [23]. This was followed by establishment of the VLC Consortium (mainly Japanese companies) in 2003, and the development of the basic theory and channel model of VLC in 2004 [21]. The IEEE recognised the potential of VLC technology by producing IEEE Standard 802.15.7 in 2011 [24, 25], which defines physical and the media-access-control (MAC) layers for a short range VLC in an optically transparent media to support audio and video multimedia services. More recently researchers have been investigation organic based LEDs with large area white panels and high brightness efficiency, and photodetectors for VLC [26].

1.3 Existing and Envisioned Application Areas

Variations of OWC can be potentially employed in a diverse field of communication applications ranging from optical interconnects within integrated circuits through terrestrial links to satellite communications. Figure 1.2 provides a

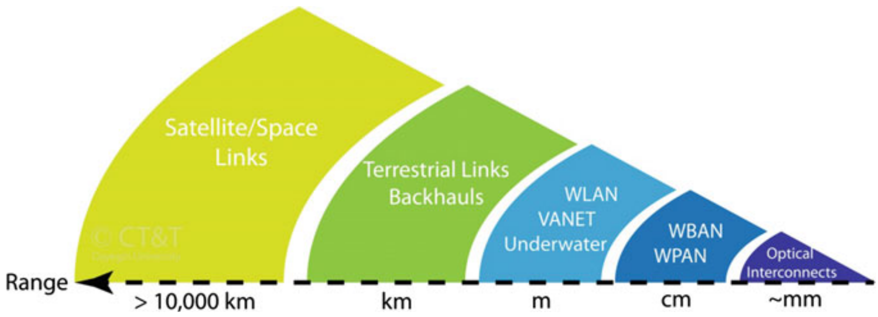

Fig. 1.2 Categorization of OWC applications based on the transmission range

categorization of OWC applications based on the transmission range. Some of these applications exist and are already commercially available while some are envisioned for future use. The two mainstream application areas of OWC are the last-mile broadband access network and office interconnection. In such applications, state-of-the-art OWC systems can support 10 Gbps Ethernet, which equals the bandwidth provided by metro fiber optic systems and is significantly higher than the 60 GHz RF wireless based 1.25 Gbps Ethernet systems. Another major application area of OWC is in personal communication systems. The current state-of-the-art in personal communications is Gigabit Infrared (Giga-IR) that operates at over a short range at data rates of 512 Mbps and 1.024 Gbps. OWC is also being used in indoor (as part of the VLC for the 5G WCS) and ultra-long range (i.e., FSO) systems. Underwater OWC is another applications area offering a data rate up to several hundred Mbps over typical transmission ranges up to a few metres [27].

The increased growth in population and mobility are leading many countries to re-think of their present and future city planning, especially focusing on integrated socio-economic infrastructure supported by sustainable development. To support evolving dynamics in modern urban environments the city planners are aiming to establish comprehensive information and communication technology (ICT) infrastructure, which includes the intelligent transportation systems. This allows creation of a smart city, where people, government, economy and environment are seamlessly connected. Current infrastructures such as universities, airport, train and bus stations, hospitals, airports, government institutions, power stations, etc. are now connected via distributed networks (wired and wireless), where the information is distributed and shared between organisations. However, these distributed wireless communications networks are facing a growing increase in the data flow, where the existing RF based WCS do not have the required bandwidth allocation to fulfil this growing trend. To address this problem and release the pressure on the RF spectrum OWC technologies could be effectively used in dedicated applications such as M2M, healthcare, vehicle to vehicle communications, autocells in 5G WCS, etc. In particular, besides indoor illumination, LEDs will be widely used in outdoor lamps, traffic signs, advertising displays, intelligent transport systems, etc. This would make possible the extensive deployment of VLC for a wide range of short- and medium-range communication applications including wireless local, personal, and body area networks (WLAN, WPAN, and WBANs), vehicular networks, indoor localization and navigation (where current GPS is not available), underwater networks and M2M communication among others offering a range of data rates from a few Mbps to a few Gbps.

1.3.1 Ultra Short Range OWC Applications

Demands for exascale computing and the concepts of super-computers and powerful data centres and system-on-chip (SoC) require unconventional methods for inter-chip and intra-chip communications. In 1988 the first power and speed comparisons between optical (based FSO) and electrical interconnects were reported in [28]. Since then several technological developments have been introduced and FSO based connections adopted in board-to-board connection [29] and inter-chip applications [30]. In [31] commercial 850 nm GaAs vertical-cavity-surface-emitting-lasers and fabricated fused silica microlenses were used for 3-D integrated structure on top of the substrate, whereas a design of a fully distributed interconnect architecture based on FSO was proposed in [32]. With superior features such as high bandwidth, low latency, more complex and low power consumption optical interconnects have been proposed as an alternative to copper-based electrical interconnects for data centres (DCs), since standard electrical interconnections have become a major bottleneck in data centre DC system design [33–35]. The use of optical network-on-chip (O–NoC) is particularly advantageous in space applications, which are characterized by the need to very high data rates (on the order of Tbps), robustness against electromagnetic interference, and stringent power consumption constraints. For instance, at such high data rates, more than 90 % of power consumption can be saved by using optical instead of metallic interconnects [36]. Optical interconnects can be implemented either as guided or unguided (free space) wave. In guided optical interconnects, waveguide loss, cross-section and minimum bend radius dominate the design process. Free space optical interconnects (FSOI) [37], see Fig. 1.3, provide a more flexible solution and can achieve a high degree of parallelism, since they allow multi-dimensional device arrays to be interconnected to each other. For example, a FSO based inter-rack network with high flexibility (FIREFLY) was proposed in [38], which utilises OWC based architectures for the DC replacing the inter-rack fibre connections. DC switches equipped with a number of steerable FSO transmitters were used to establish links between racks.

As can be seen ultra-short scale wireless optical interconnects promise high industrial interest. A recent market report predicts that chip-level optical interconnect market will total almost $520 million by 2019 going on to reach $1.02 billion by 2021 [39]. The share of FSOI within the overall optical interconnect market will be mainly determined by if and how efficiently misalignment tolerance can be addressed.

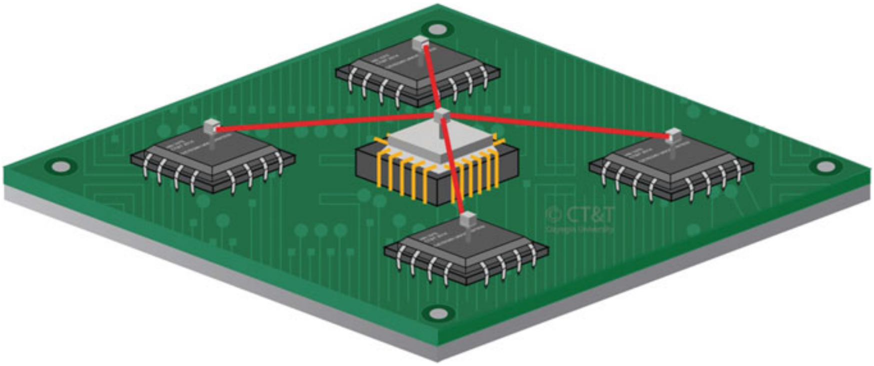

Fig. 1.3 VLC chip-to-chip

1.3.2 Short Range OWC Applications

A typical short range (on the order of tens of centimeters) wireless application is the wireless body area network (WBAN) [40], which involves the use of wearable computing devices/sensors and retrieval of physical and bio-chemical information from the individual. In a typical WBAN, there are several sensor units placed inside or on the human body, which collect vital health signs such as blood pressure, heart rate, glucose, etc. These sensors are wirelessly connected to a central unit which has access to outside network. While coexisting with other wireless networks, such WBANs have to ensure a high quality of service for transmitting health information. The IEEE 802.15.6 task group is one of the first to work on the standardization of RF-based WBANs [41]. Indeed, current WBANs are typically RF based, e.g. using ultra-wide band (UWB) transmissions. But their use might be problematic in medical facilities and hospitals where RF deployment is restricted or prohibited due to electromagnetic interference (EMI) [42]. This is because the EMI can cause malfunctioning of these networks, and in addition, the effect on health of long-time exposure to RF signals is still undetermined. On the other hand, the propagation of RF waves in/on the human body is very complex to investigate. Within this context, OWC is a promising alternative to the RF-based solutions [43, 44]. For instance, the use of the VLC technology for simultaneous transmission of electrocardiography (ECG) signal and patient information was studied in [45]. Some medical testing equipment such as cardio stress test (Fig. 1.4) can be also re-designed by integrating LEDs on sensor units and VLC links can replace the large number of cables required in such equipment. The recent developments in organic LED (OLED) technology represent a major advancement making possible to integrate VLC transceivers into wearable devices and clothing as a part of WBAN.

Another example of short-range OWC is for indoor applications. Today there are a number of examples of augmented reality (AR), many of which are running as smart phone application. Typically an AR based smart phone application may

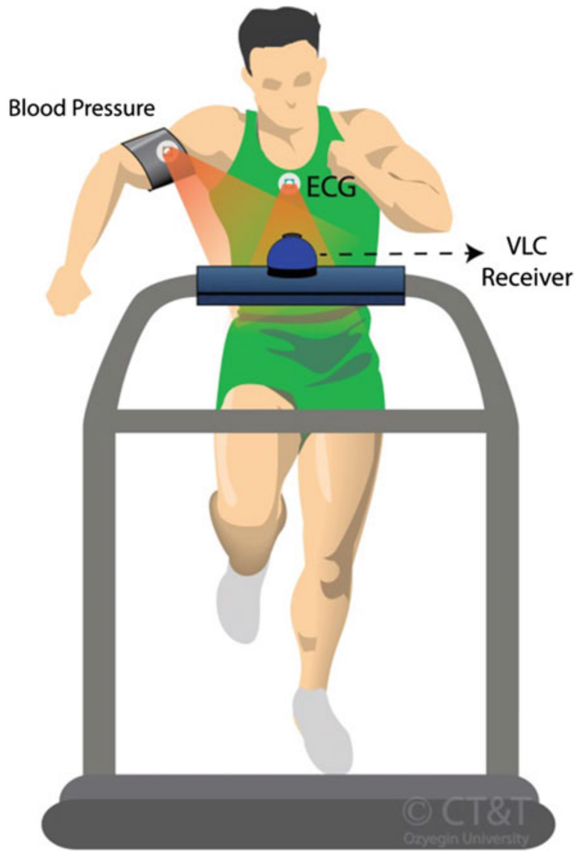

Fig. 1.4 VLC for medical applications

employ the GPS location and the digital compass for positioning and orientation. However, these sensors suffer severe errors in indoor environment or may simply not work at all. However, in indoor environments the VLC technology functions reliably to provide location and orientation data for indoor AR apps. Another short range wireless application is wireless personal area network (WPAN), which involves the "last meter" connectivity for interconnecting devices centred around an individual person's workspace, see Fig. 1.5. OWC (in the form of infrared LED communication) has been effectively used to enable WPANs since mid-1990s. The Giga-IR standard developed by the Infrared Data Association (IrDA) allows transmission of 1 Gbps while a new standard to enable the speeds of 5 and 10 Gbps is still under development. Recent research efforts in this area include smart phone camera communications [46] where the integrated phone camera (imaging sensor) is used as an optical detector to enable various M2M applications including phone-to-phone, phone-to-TV and phone-to-vending machine communication among others.

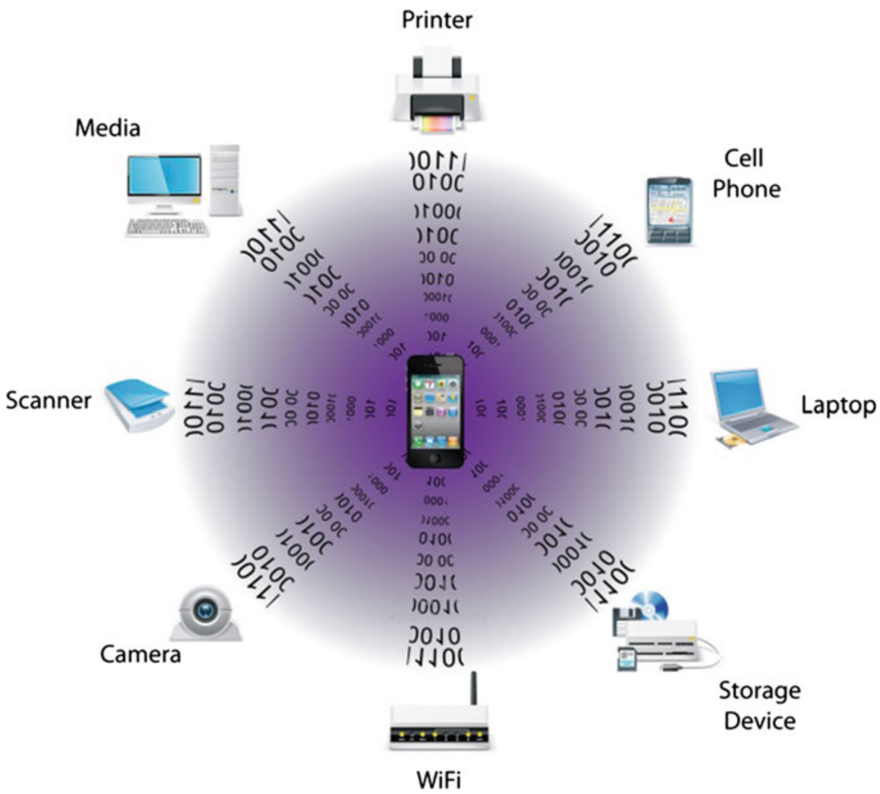

Fig. 1.5 VLC application in WPAN

1.3.3 Medium Range OWC Applications

In medium range (on the order of meters), the typical wireless application is the wireless local area networks (WLANs). In the past, indoor infrared communication was extensively investigated as a possible WLAN solution. However, the success of RF based solutions, i.e., WiFi, practically put aside infrared-based WLANs. This might however change with the emergence of VLC, also sometimes referred to as LiFi, with direct reference to its RF counterpart.

VLC capitalizes on the expected omnipresence of LED-based illumination infrastructure, see Fig. 1.6. Spatial confinement of LEDs enables high density wireless networking while minimizing interference issues. Recent research [47] has shown that the area spectral efficiency indoors can be improved by a factor of 900 when using a VLC-based WLAN. Current experimental VLC testbeds have demonstrated the feasibility of very high speeds up to 3.5 Gbps [48, 49]. Some start-up companies such as PureVLC (UK), Oledcomm (France) and Visilink (Japan) have also been exploring to commercialize this technology.

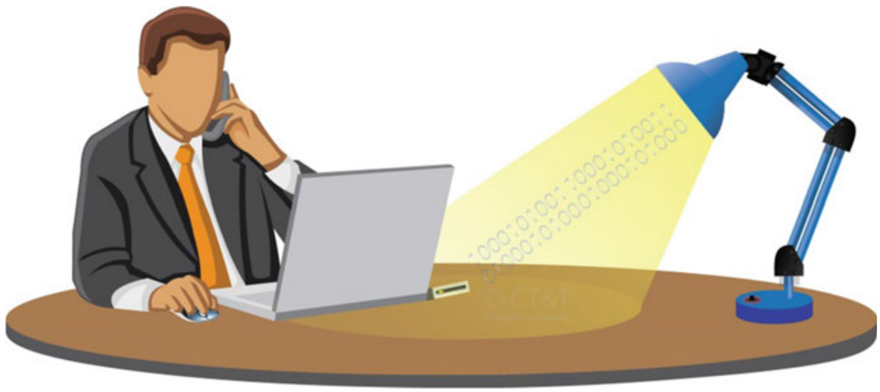

Fig. 1.6 A VLC-enabled hot spot composed of a USB dongle receiver and a desk lamp based VLC transmitter

In addition to indoor deployment, as mentioned, LEDs are being widely used in outdoor lighting, traffic signs, advertising displays, car headlights/taillights, etc., as illustrated in Fig. 1.7. This paves the way for vehicle-to-vehicle communication and vehicle-to infrastructure communication [50]. Vehicles fitted with LED-based front and back lights can communicate with each other and with the road side infrastructure, i.e., street lamps, traffic lights, through the VLC technology. Furthermore, LED-based RSI can be used for both signalling and broadcasting safety-related information to vehicles on the road. VLC is well positioned to address both the low

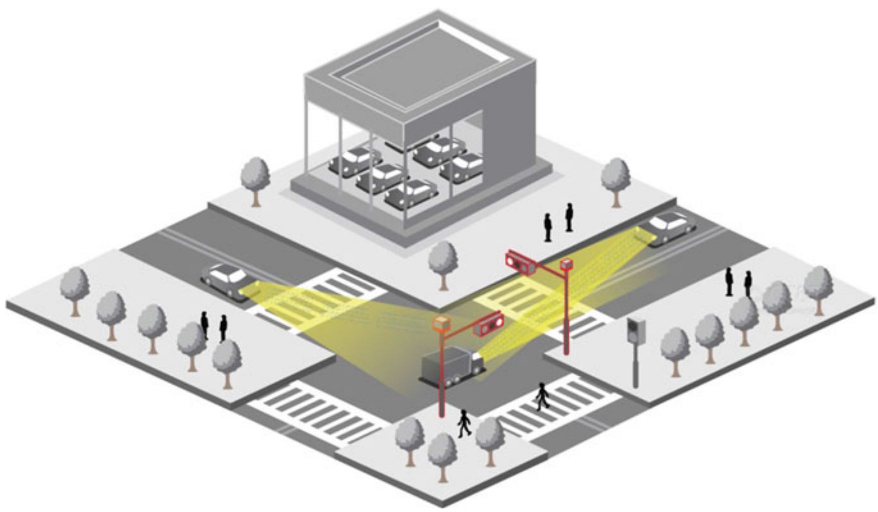

Fig. 1.7 Vehicular VLC network where vehicles communicate with each other and roadside infrastructure through their LED-based front and back lights

latency required in safety functionalities (i.e., emergency electronic brake lights, intersection collision warning, in-vehicle signage, platooning) and high speeds required in so-called infotainment applications (i.e., map downloads and updates, media downloading, point of interest notification, media downloading, high-speed internet access, multiplayer gaming, and cooperative downloading). In recent few years we have seen a growing use of smartphones, tablets, Google glasses etc., which come with built-in cameras that can be used to capture images and videos. Thus, offering huge potential to be utilized as VLC receivers [51]. VLC systems employing image sensor-based communication system or camera communication offer non-interference communication with spatial-division multiplexing, which extracts different signal from different spatial position from the captured videos or photos [52]. The cameras in smartphone mounted in vehicles can be used to capture the images of lights from the vehicles nearby as part of the intelligent transportation systems.

Another potential medium range application area of VLC is underwater communication. Traditionally, acoustic communication is used underwater and can cover long ranges up to several kilometres. However, it is well known that this technology suffers from a very small bandwidth available, very low celerity, large latencies due to the low propagation speed, and high power consumption due to large antennas used [53]. As such, data rates using underwater acoustic communication are limited to a few tens or hundreds of kbps. OWC has the potential of high data-rate transmission in the underwater environment. However, it should be noted that light suffers from high absorption rates due to the electron transitions in the far ultraviolet and to different intra/inter molecular motions in the infrared band. On the other hand, water is relatively transparent to light in the visible band of the spectrum. In fact, absorption takes its minimum value in the blue/green spectral range (450–550 nm). This paves the way for underwater VLC which is able to achieve data speeds of hundreds of Mbps for relatively short ranges (less than a 100 m) complementing long range acoustic communication. The other important challenge concerns the development of energy-efficient solutions for transmitter/receiver localization and beam alignment through the use of smart transceivers capable of self-adapting to environmental conditions [54].

1.3.4 Long Range OWC Applications

Gigabit Ethernet backhauling solutions in next generation 4G and 5G wireless networks will largely be based on the millimeter-wave (MMW) and licensed E-Band technologies (i.e., 50/60 and 80 GHz bands, respectively), for supporting bandwidth-intensive data operations in the enterprise and urban markets with shorter link requirements of 3–5 km [55]. Nonetheless, the high susceptibility of MMW radios to the rain attenuation presents a greater challenge to network operators in optimizing their backhaul solutions, to deliver GigE speeds with a desired carrier-grade availability of 99.999 %, not affected by local meteorological

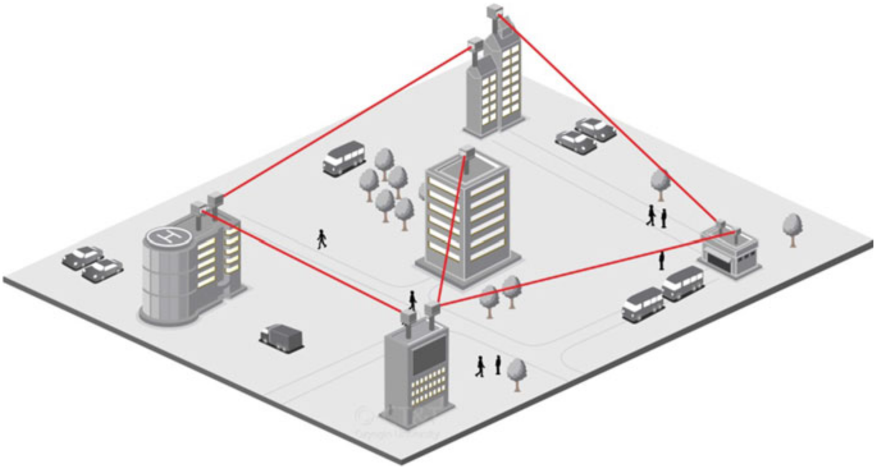

Fig. 1.8 FSO link for inter-building connections

conditions [56, 57]. FSO communications is a promising broadband wireless access candidate in complementing the RF solutions to resolve the existing “last mile” access network problems (i.e., bridging the gap between the end user and the fiber optic infrastructure already in place), see Fig. 1.8. In comparison to RF counterparts, an FSO link has a very high optical bandwidth available, allowing aggregate data rates on the order of Tbps [19]. FSO systems have initially attracted attention as an efficient solution for the “last mile” problem to bridge the gap between the end user and the fiber optic infrastructure already in place. As such, hybrid FSO/fiber bidirectional links are an appropriate solution for fiber-to-the-home (FTTH) applications, see Fig. 1.9, for example. In such applications the last meters are performed by a high capacity FSO link in sites where there are no telecommunications cabling already installed. Links between offices of the same company in a building to building scenario or in a university campus are the perfect examples of the application of FSO links with high capacity hybrid links. Recently 1.6 Tbps data transmission between building-to-building using 16-wavelength each at 100 Gbps [19] and a 120 Gbps hybrid link for passive optical access networks were reported [58, 59].

Telecom carriers have already made substantial investments to augment the capacity of their fiber backbones. To fully utilize the existing capacity, and therefore generate revenue, this expansion in the backbone of the networks should be accompanied by a comparable growth at the network edge where end users get access to the system. FSO systems can be also used for a number of long-range communication applications including cellular backhauls, wireless metropolitan area network (WMAN) extensions, WLAN-to-WLAN connectivity in enterprise and campus environments, broadband access to remote or underserved areas, and wireless video surveillance/monitoring. Since FSO links are easy-to-install and redeployable, they are particularly useful as redundant links in disaster situations

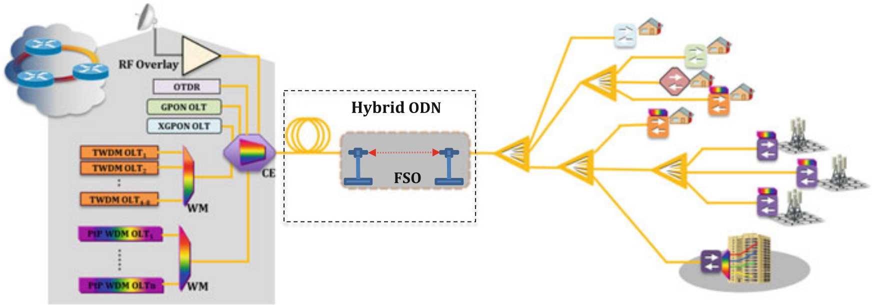

Fig. 1.9 Schematic figure of a scenario where FSO communications link in optical distribution networks (ODN) can make part yielding high data rates

where local infrastructure could be damaged or unreliable. A tragic example of the FSO deployment efficiency as a redundant link was witnessed after 9/11 terrorist attacks in New York City. FSO links were rapidly deployed by financial corporations in Wall Street region which were left out with no landlines. Further details on FSO communication and recent research activities in this area can be found in the comprehensive survey presented in [17].

The performance of both FSO and RF links are susceptible to the adverse effects of meteorological and other natural conditions. Research studies [60–62] have shown that the media diversity scheme presents a more viable and effective mitigation technique under extreme weather conditions, which involves the utilization of a lower data-rate RF channel in conjunction with the FSO channel (i.e., hybrid RF/FSO). Correspondingly, hybrid FSO/RF systems promote the extension of link range while maintaining a desired availability, and ensuring a minimum data communication when the primary FSO link is down due to the fog. With the enhanced duality feature to switch between the two technology options, this approach potentially avoids link outages under all weather condition. The rationale pertaining to the development of such hybrid FSO/RF systems, see Fig. 1.10, is based upon theoretical and experimental validations, which reflect the symbiotic relationship between these two technologies, since fog and rain drastically affect the FSO and RF links, respectively, but only insignificantly vice versa, and they rarely occur simultaneously.

While earlier uses of FSO links were mainly for fixed installations, it is possible to establish such links in mobile applications given that reliable pointing-acquisition-tracking algorithms are designed. This would enable the deployment of FSO links for aircraft-to-aircraft, aircraft-to-ground, aircraft-to-high altitude platforms (HAPs), as illustrated in Fig. 1.11. Such uses of FSO are particularly useful in tactical field and research is pursued in this direction by military organizations and defence companies [63].

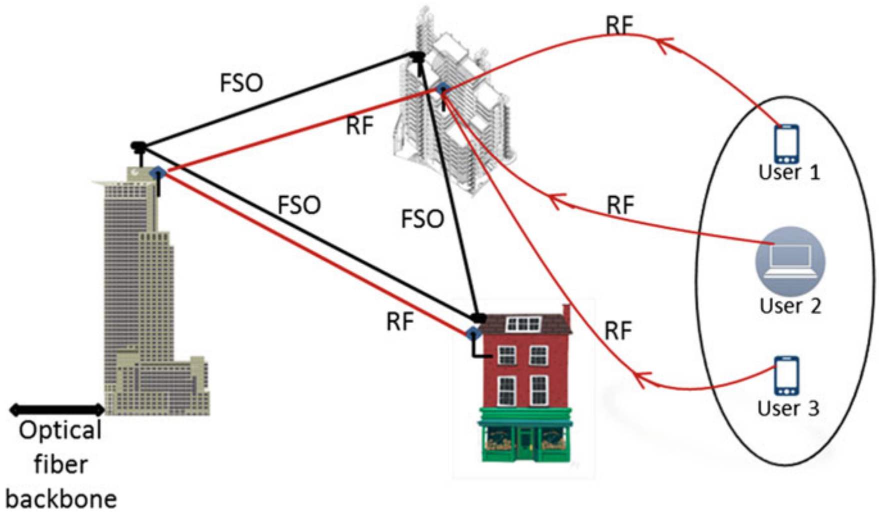

Fig. 1.10 Hybrid RF/FSO communications link

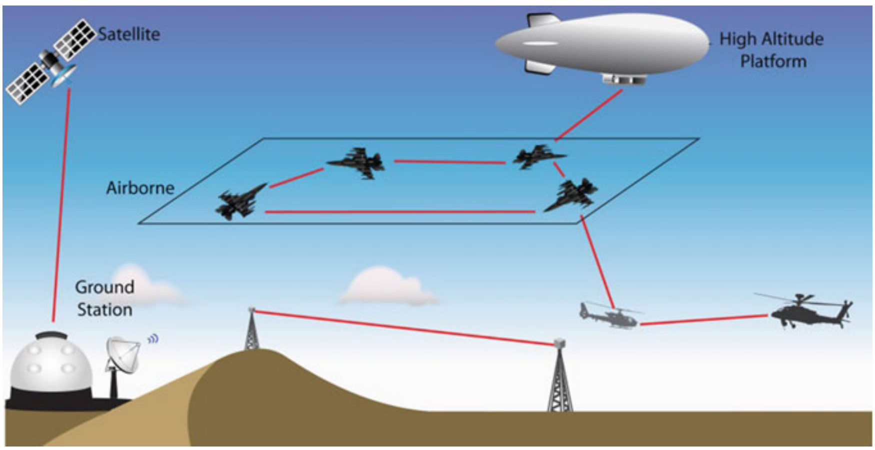

Fig. 1.11 FSO for aircraft-to-aircraft, aircraft-to-HAP, aircraft/satellite/HAP-to-ground communications

1.3.5 Ultra Long Range OWC Applications

Aeronautical and space communications may strongly benefit from current laser communications research and development. The motivation for using frequencies for aeronautical and space applications in the optical spectrum is fundamental. For equal antenna sizes, the advantages of shorter wavelengths becomes obvious as the received signal strength is inversely proportional to the square of the wavelength, i.e., the coupling efficiency is significantly higher and antennas may be constructed to be much smaller. Aerospace FSO system also benefits from current advances made in the optical fiber communication technology since a number of devices could readily be used in FSO systems for tropospheric and aerospace applications.

There are a number of applications for FSO in the field of aerospace communications including space-ground links, space air links, space-space links and air-ground links. Earliest research on space laser communications was undertaken in the USA within the framework of different development programs, which dealt with research on laser sources and the terminal technology [64]. The early research and development in Europe resulted in a satellite system for data transmission between a LEO (Spot-4) and a GEO (Artemis) satellite within the SILEX (Semiconductor Inter-satellite Link Experiment) project [65]. Furthermore, the development and setup of an optical ground station on the astronomical site in Tenerife [66] was used to carry out in-orbit verification and space-ground measurement campaigns. The Artemis satellite was also used for experiments with the Japanese OICETS (Optical Inter-Orbit Communications Engineering Test Satellite) satellite [67]. This satellite also acted as test source for a variety of LEO-ground measurements campaigns with ground station in Japan, Germany, Tenerife and the USA [68–70].

FSO has also been used as a powerful ultra-long (>10000 km) link for ground-to-satellite and satellite-to-satellite communications as well as intraplanet communications. In 2001, a 50 Mbps FSO link was successfully established between the ARTEMIS geostationary satellite and the SPOT-4 French Earth observation satellite in the sun-synchronous low earth orbit [71]. The European data relay system (EDRS) [72] is a satellite system currently under development, which will be used to relay information to and from non-geostationary satellites, spacecraft, other vehicles and fixed Earth stations. It deploys three GEO satellites, equipped with OWC inter-satellite links and Ka-band links for the space-to-ground link. In 2013, NASA's Lunar laser communication demonstration, which used a FSO link between Moon to Earth was demonstrated offering a data rate of 622 Mbps over a transmission span of 384,600 km [73]. It is expected that OWC will continue to be a major enabling technology in space and satellite links.

Coherent systems are also matter of research and development since they offer higher sensitivity and spectral efficiency at the cost of increased complexity [74]. In practice, for links passing through the atmosphere, clear-air turbulence will induce serious phase distortions and fading, thus affecting the performance of coherent receivers. The impact of phase distortions and scintillation can be mitigated by use of array receivers or adaptive optics [75]. A coherent system was experimentally demonstrated between two terminals on the LEO satellites TerraSAR-X and NFIRE (near field infrared experiment) [76]. In-orbit verification was also carried out with LEO-ground experiments. These types of laser terminals are now integrated in various satellites that can therefore make use of EDRS which will be in operation soon [77]. Inter-satellite laser links and Ka-band satellite-ground links are combined with the relay Earth observation data from LEO via GEO to ground. Also optical feeder links from the ground to GEO particularly Tbps systems are under investigation [78]. There also a number of researches work on the LEO-ground systems including the "optical payload for Lasercomm science" terminal on the international space station [79], the Russian "on-board laser communication terminal" also on the ISS [80] and the Chinese satellite Haiyang 2. The longest FSO link to date was demonstrated between moon and Earth with a laser terminal on the "lunar atmosphere and dust environmental explorer" satellite [81].

Aside air-to-air connections, air-to-ground links are also of interested for various applications, for example for transmission of sensor data for traffic monitoring or surveillance. Airborne terminals were tested and demonstrated in various experiments involving different aircraft, where tracking and communications were achieved using optical terminals installed in a Boeing 767-200 [82], a BAC 1-11 aircraft [83], an Altair unmanned aerial vehicle [84], and a tornado jet fighter [85].

1.4 Conclusions

Utilization of the optical band, which includes IR, visible and UV frequencies, for wireless transmission opens doors of new opportunity in areas as yet largely unexplored. This chapter provided an overview of this emerging technology focusing on the historical development and current status, as well as existing and envisioned applications areas from the ultra-short range to the ultra-long range.

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