Signals and Communication Technology

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Optical Wireless Communications

An Emerging Technology

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Preface

The proliferation of wireless communications stands out as one of the most significant phenomena in the history of technology. Wireless devices and technologies have become pervasive much more rapidly than anyone could have imagined and they will continue to be a key element of modern society for the foreseeable future. Today, the term "wireless" is used almost synonymously with radio frequency (RF) technologies as a result of the wide-scale deployment and utilization of wireless RF devices and systems. With the ever-growing popularity of data-heavy wireless communications, the demand for RF spectrum is outstripping supply and the time has come to seriously consider other viable options for wireless communication using the upper parts of the electromagnetic spectrum for applications where access to huge bandwidth is a requirement.

Utilization of the optical band of the electromagnetic spectrum for wireless transmission opens doors of opportunity in areas as yet largely unexplored. Optical frequencies range from 300 GHz to 300 petahertz (PHz) and include infrared, visible and ultraviolet bands—a spectral range that dwarfs the 300 GHz that the RF band represents. Optical wireless communication (OWC) systems offer significant technical and operational advantages such as higher bandwidth capacity, robustness to electromagnetic interference, inherent security, low power requirements and unregulated spectrum. Variations of OWC can be employed in a diverse range of communication applications from very short-range (in the order of millimeters) optical interconnects within integrated circuits through outdoor inter-building links (on the order of kilometers) to satellite communications (larger than 10,000 kms).

With its significant advantages and wide range of application areas, OWC is one of the most promising current opportunities for high-impact research in the information and communication technology area. However, in many respects, OWC technology is still in its infancy and calls for consolidated research efforts to harness the enormous potential of the optical spectrum for communication applications. With the aim to build a European scientific network on OWC, the COST IC1101 Action "Optical Wireless Communication—An Emerging Technology (OPTICWISE)" was launched in November 2011 for 4 years. COST (European

Cooperation in Science and Technology) is one of the longest running European frameworks supporting cooperation among scientists and researchers across Europe. OPTICWISE has been the very first COST Action dedicated solely to this emerging field with enormous potential and brought together more than 150 researchers from European academic and research institutions, government bodies and companies involved in two major OWC sub-fields, namely free space optical communication (FSO) and visible light communication (VLC).

OPTICWISE has played a key role in synergizing the interdisciplinary scientific expertise of European researchers in various scientific disciplines including the electromagnetic propagation theory, atmospheric physics, information/communication theory, networking, communication systems, photonic components, devices and systems. Through integrated research capability made possible by the OPTICWISE, Action participants have explored and developed novel methods, models, techniques, strategies, and tools in infrared, visible, and ultraviolet spectral bands. This resulted in a large number of joint publications. Such contributions have led to a much better understanding of OWC which was treated as a niche technology in the past. In addition to theoretical contributions, several Action participants have contributed to the design and building of proof-of-concept VLC and FSO systems demonstrating the promise of OWC systems for achieving low-cost, ultra-high bandwidth, and reliable future generation heterogeneous communication networks.

To document on the one hand the multidisciplinary research carried out within COST IC1101 and on the other hand to encourage newcomers to this emerging field, this book introduces researchers, practitioners, graduate, and postgraduate students to the diverse research on OWC in a comprehensive manner. The book starts with an introductory chapter, which provides an overview of OWC field highlighting different sub-fields and major application areas. The rest of the book is categorized into four main parts. The first part (Chaps. 2–8) consists of chapters which deal with the propagation modeling and channel characterization of OWC channels at different spectral bands/applications. The second part (Chaps. 9–19) starts with a chapter that provides a unified information-theoretic treatment of OWC and then continues with the chapters on advanced physical layer methodologies to approach these ultimate limits under practical constraints. On the top of physical layer is the upper-layer protocols and cross-layer designs, which are dealt in the third part of the book (Chaps. 20–24). The last part of the book (Chaps. 25–28) features chapters each of which focuses on different OWC applications.

I would like to thank all authors and reviewers for the contributions. Without their voluntary help it would have been impossible to publish this book. I would also like to thank my co-editors of this book, Carlo Capsoni, Zabih Ghassemlooy, Anthony Boucouvalas, and Eszter Udvary who made most of the editorial job. We also are grateful to COST for supporting our Action in general and the dissemination of this book in particular.

Istanbul, Turkey

Prof. Dr. Murat Uysal
COST IC1101 Chair

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COST (European Cooperation in Science and Technology) is a pan-European intergovernmental framework. Its mission is to enable break-through scientific and technological developments leading to new concepts and products and thereby contribute to strengthening Europe's research and innovation capacities. It allows researchers, engineers and scholars to jointly develop their own ideas and take new initiatives across all fields of science and technology, while promoting multi- and interdisciplinary approaches. COST aims at fostering a better integration of less research intensive countries to the knowledge hubs of the European Research Area. The COST Association, an International not-for-profit Association under Belgian Law, integrates all management, governing and administrative functions necessary for the operation of the framework. The COST Association has currently 36 Member Countries (www.cost.eu).

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Contents

Chapter 1
An Overview of Optical Wireless Communications

Z. Ghassemlooy, M. Uysal, M.A. Khalighi, V. Ribeiro, F. Moll, S. Zvanovec and A. Belmonte

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

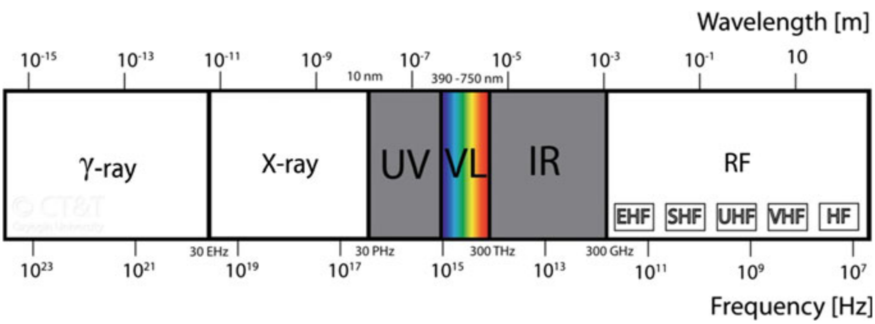

Fig. 1.1 The electromagnetic spectrum

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

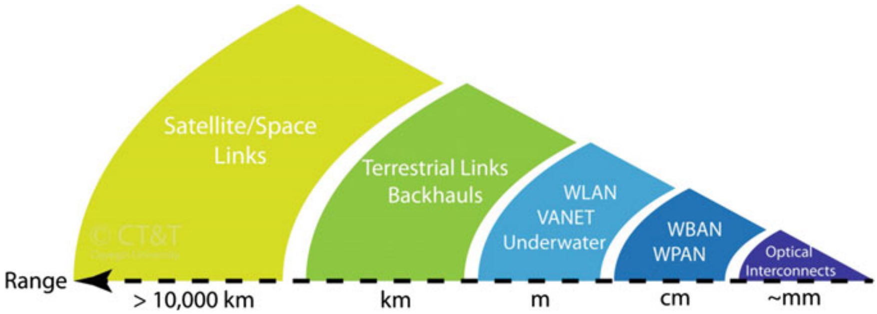

Fig. 1.2 Categorization of OWC applications based on the transmission range

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.

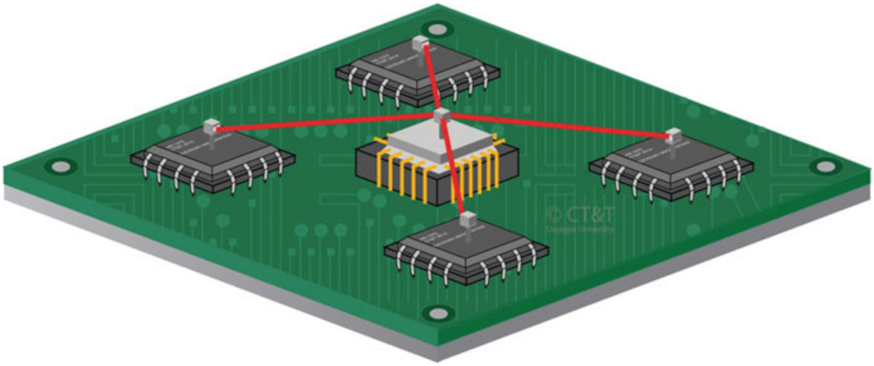

Fig. 1.3 VLC chip-to-chip

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