Optical Wireless Communications – An Emerging Technology[1]

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ABSTRACT
Optical wireless communication (OWC) enables wireless connectivity using infrared, visible or ultraviolet bands. With its powerful features such as high bandwidth, low cost and operation in an unregulated spectrum, OWC can be, in some applications, a powerful alternative to and, in others, complementary to the existing wireless technologies. It is one of the most promising current areas of research with significant potentials for high-impact results which will considerably change the wireless market mostly dominated by the radio-frequency (RF) technologies. In this paper, we provide an overview of OWC highlighting the advantages and wide range of application areas of this emerging technology.
Keywords: optical wireless communication, free space optical communication, visible light communication, ultraviolet communication.

1. INTRODUCTION

Wireless technologies are one of the great success stories in the history of technology, realizing the dream of humans to communicate from anywhere at anytime. While voice communication 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 communication experience with much richer multimedia content. Wireless devices, applications and services have already radically changed the way we live, work, and socialize. The emerging concept of Internet of Things further promises wireless connectivity among machines, sensors and virtually any objects 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 communication an integrated part of human life.

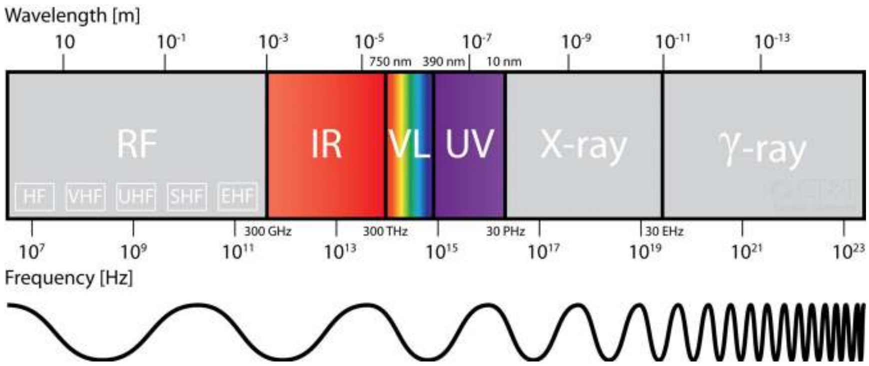

Figure 1. Electromagnetic spectrum.

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 in the market. The RF band lies between 30 kiloHertz (kHz) and 300 GigaHertz (GHz) of the electromagnetic spectrum and its use is strictly regulated by the local and international authorities. In most cases, sub-bands are exclusively licensed to operators, *e.g.*, cellular phone operators, television broadcasters, point-to-point microwave links *etc*. With the ever-growing demand for data-heavy wireless applications and services, the demand for the RF spectrum is outstripping the supply, thus leading to the spectrum congestion. In the light of the spectrum bottleneck at both the network access and backhaul levels, the time has come to seriously consider the upper parts of the electromagnetic spectrum for wireless communications. By doing so, we move into the optical band which includes **infrared (IR)**, **visible (VL)** and **ultraviolet (UV)** sub-bands, see Fig. 1. The use of these bands for communications purposes offers unique opportunities, which remain mostly unexplored so far. In comparison to the RF counterparts, optical wireless communications (OWC) [1] enjoys superior features such as ultra-high bandwidth, robustness to electromagnetic interference, a high degree of spatial confinement bringing virtually unlimited reuse, and inherent physical security. Furthermore, since they operate in the unregulated spectrum, no licensing fee is required thus leading to a cost-effective solution.

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The term OWC refers to any optical transmission in an unguided media although its variations based on the operating 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 light emitting diodes (LEDs) which can be pulsed at very high speeds without noticeable effect on the lighting output and human eye. The dual use of LEDs for illumination and communication purposes is a sustainable and energy-efficient approach and has the potential to revolutionize how we use light. VLC can be possibly used in a wide range of applications including 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 (750 – 1600 nm). 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. 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.

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 [2]. In late 19th 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 20th 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 meters. 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. 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.

In modern sense, LEDs or lasers are used as light sources in OWC systems. In July 1960, just months after the first public announcement of the working laser, Bell Labs was able to transmit signals 40 km away using a ruby laser [3]. In November 1962, Hughes Research Labs used a helium-neon laser excited by an HF amateur radio transmitter and sent voice signals to a distance of 30 km. In 1963, North American Aviation demonstrated the first transmission of TV signal using OWC. A comprehensive list of OWC experimental demonstrations during 1960-1970 is reported in [4]. 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 1970's, they became the obvious choice for long distance optical transmission and shifted the focus away from OWC systems.

Over the decades, the main focus of OWC related activities was covert military communications [5] and space applications including inter-satellite and deep-space links. OWC's mass market penetration has remained limited with the exception of IrDA [6] which became a highly successful wireless short-range transmission solution in 1990's and some success of FSO links particularly as a redundant link where fiber optic installations are not possible or feasible.

In recent years, particularly with the emergence of VLC, the OWC market has begun to show future promise. In line with the governmental plans worldwide to phase out incandescent light bulbs in favor of more energy-efficient lighting solutions, it is predicted that LEDs will be the ultimate light source in the near future. Besides indoor illumination, LEDs will be widely used in outdoor lamps, traffic signs, advertising displays, car headlights/taillights, *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, underwater networks and machine-to-machine (M2M) communication among others.

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 [14] 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 [7, 8]. 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.

3. EXISTING AND ENVISIONED APPLICATION AREAS

Variations of OWC can be potentially employed in a diverse range of communication applications ranging from optical interconnects within integrated circuits through terrestrial links to satellite communications. Figure 2 provides a 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.

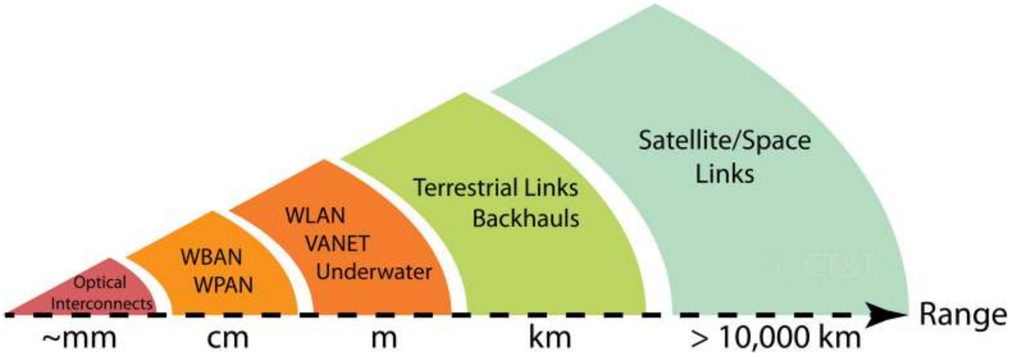

Figure 2. Categorization of OWC applications based on the transmission range.

3.1. Ultra Short Range OWC Applications

Demands for exascale computing and the concept of super-computers require unconventional methods for inter-chip and intra-chip communications. With superior features such as high bandwidth and low latency, optical interconnects [9] have been proposed as an alternative to copper-based electrical interconnects which have become a major bottleneck in system design. 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) [10], see Fig. 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. 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 [11]. The share of FSOI within the overall optical interconnect market will be mainly determined by if and how efficiently misalignment tolerance can be addressed.

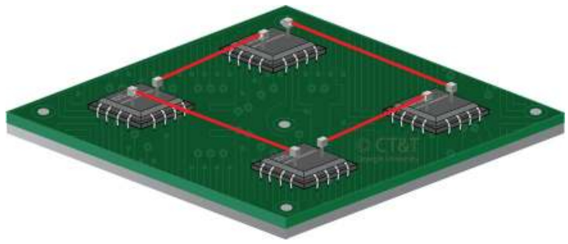

Figure 3. Illustration of free space optical interconnect.

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) 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 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. Current WBANs are typically RF based, but their use might be problematic in medical facilities and hospitals where RF deployment is restricted or prohibited due to electromagnetic interference (EMI). Particularly, the recent developments in organic LED (OLED) technology represents a major advancement making possible to integrate VLC transceivers into wearable devices and clothing as a part of WBAN. Some medical testing equipment such as cardio stress test (Fig. 4) can be also re-designed integrating LEDs on sensor units and VLC links can replace the large number of cables required in such an equipment.

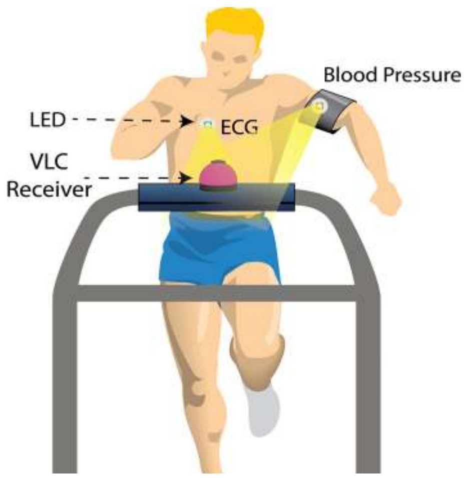

Figure 4. An envisioned cardio-stress test equipment based on VLC. The LEDs attached to sensor units communicate wirelessly with the receiver located on the equipment handle bar.

Another short range wireless application is wireless personal area network (WPAN) which involves the "last meter" connectivity for interconnecting devices centered around an individual person's workspace. 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 [20] 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.

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, in the WLAN market is obvious. This might however change with the emergence of VLC, also sometimes referred to as LiFi, with direct reference to its RF counterpart. The emergence of VLC is in fact a result of recent development in solid state lighting technologies. New generations of 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.

Figure 5. A VLC-enabled hot spot where the VLC receiver in the form of an USB dongle communicates with the desk lamp acting as a VLC transmitter.

VLC capitalizes on the expected omnipresence of LED-based illumination infrastructure, see Fig. 5. Spatial confinement of LEDs enables high density wireless networking while minimizing interference issues. Recent research [23] 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 demonstrated the feasibility of very high speeds up to 3.5 Gbps [12, 13]. Some start-up companies such as PureVLC (UK), Oledcomm (France) and Visilink (Japan) have also been exploring to commercialize this technology.

In addition to indoor deployment, LEDs are being widely used in outdoor lighting, traffic signs, advertising displays, car headlights/taillights, *etc*., as illustrated in Fig. 6. This paves the way for vehicle-to-vehicle communication and vehicle-to infrastructure communication [21]. Vehicles fitted with LED-based front and back lights can communicate with each other and with the road side infrastructure (RSI), *i.e.*, street lamps, traffic lights, through the VLC technology. Furthermore, LED-based RSI can be used for both signaling and broadcasting safety-related information to vehicles on the road. VLC is well positioned to address both the low latency required in safety functionalities (*i.e.*, emergency electronic brake lights, intersection collision warning, in-vehicle signage, platooning) and high speeds required in so-called infotainment applications (*i.e.*, map downloads and updates, media downloading, point of interest notification, media downloading, high-speed internet access, multiplayer gaming, and cooperative downloading).

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 kilometers. However, it is well known that this technology suffers from a very small bandwidth available, very low celerity, and large latencies due to the low propagation speed. As such, data rates using underwater acoustic communication are limited to a few hundreds or thousands of kbps. OWC can be potentially used underwater. 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 nm-550 nm). This paves the way for underwater VLC which is able to achieve data speeds of hundreds of Mbps for short ranges (less than a hundred meter) complementing long range acoustic communication.

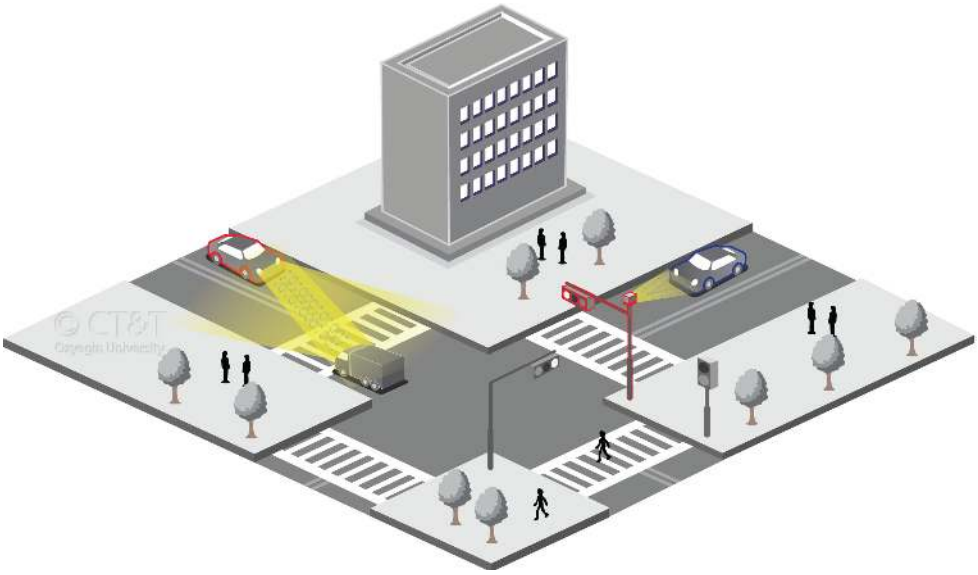

Figure 6. Vehicular VLC network where vehicles communicate with each other and roadside infrastructure through their LED-based front and back lights.

3.4. Long Range OWC Applications

FSO systems are used for high rate communication between two fixed points over distances up to several kilometers (see Fig. 7). In comparison to RF counterparts, an FSO link has a very high optical bandwidth available, allowing aggregate data rates on the order of Tbps [8]. 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. 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 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 [14].

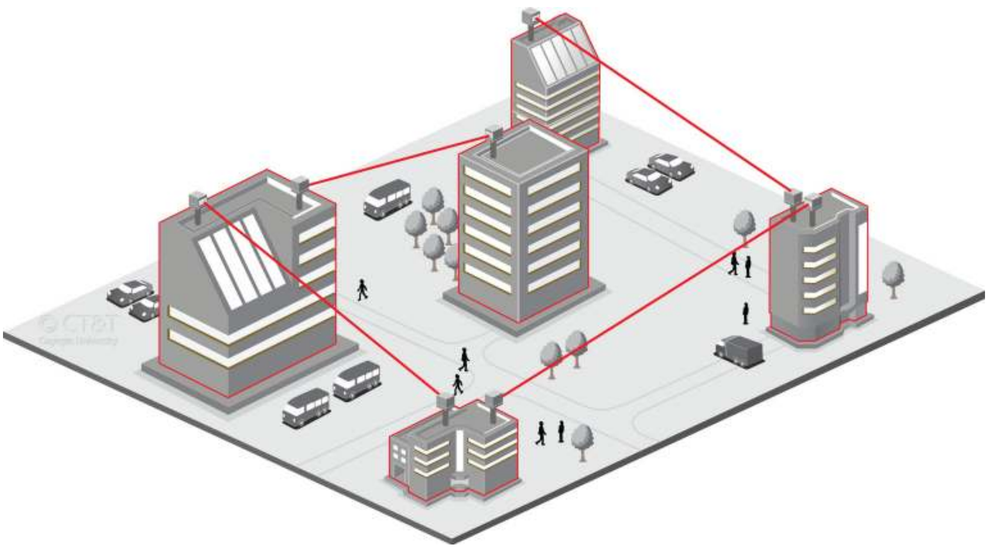

Figure 7. FSO link for inter-building connections.

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. 8. Such uses of FSO are particularly useful in tactical field and research is pursued in this direction by military organizations and defence companies [15].

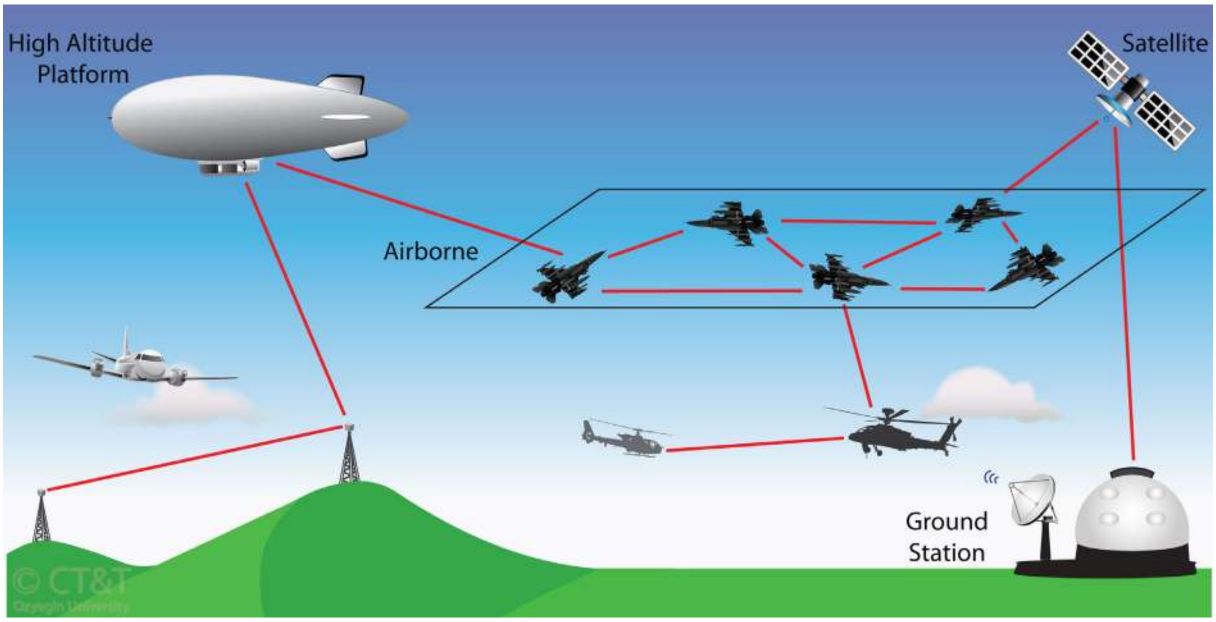

Figure 8. FSO can be deployed to support aircraft-to-aircraft, aircraft-to-HAP, aircraft/satellite/HAP-to-ground communication.

3.5. Ultra Long Range OWC Applications

FSO can be used as a powerful ultra-long connectivity solution (for more than 10000 kilometers) for ground-to-satellite and satellite-to-satellite communications as well as intraplanet communication. One of the major milestones in this area took place in 2001 when a 50 Mbps FSO link was successfully established between ARTEMIS geostationary satellite and the SPOT-4 French Earth observation satellite in sun-synchronous low earth orbit [16]. With the introduction of coherent modulation techniques, data rates on the order of Gbps were further achieved [17]. The European Data Relay System (EDRS) [18] is a satellite system currently under development to relay information to and from non-geostationary satellites, spacecraft, other vehicles and fixed Earth stations. It deploys three GEO satellites, equipped with OWC intersatellite links and Ka-band links for the space-to-ground link. Recently, in October 2013, NASA's Lunar Laser Communication Demonstration, a FSO link between Moon to Earth was established and an impressive data rate of 622 Mbps was achieved over a distance of 384600 km [19]. It is expected that OWC will continue to be a major enabling technology in space and satellite links.

4. CONCLUSIONS

Utilization of the optical band, which includes infrared, visible and ultraviolet frequencies, for wireless transmission opens doors of opportunity in areas as yet largely unexplored. This paper has provided an overview of this emerging technology with an emphasis of existing and potential application areas.

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