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Introduction

1.1 Motivation

Optical wireless communications (OWC) has become an increasingly important research area. The potential of solving complicated communications problems, such as the shortage of radio frequency (RF) spectrum, interference, and the necessity of transmission at very high data rates by optical wireless systems has seen vast improvement. Optical wireless links can establish communications channels even millions of miles apart, as evidenced by the use of optical links in space exploratory missions by NASA [1]. For shorter terrestrial distances, optical wireless links in outdoor free space are a good choice for establishing pointed links a couple of miles apart. On a much smaller scale, the existence of millions of remote controls that operate using infrared light-emitting-diodes (LEDs) is a proof of the usefulness of optical wireless systems.

Apart from the various applications of OWC that are currently in use, probably the main motivating factor to focus on this area is the possibility of mitigating the increasing spectrum shortage issue. As consumption of high data rate multimedia materials is increasing day by day and the use of handheld devices is becoming more and more widespread, the precious RF spectrum range of about 1.9 GHz that is used for mobility is getting scarcer [2]. Users are encouraged to shift to the Wi-Fi bands instead of the bands used for cellular services in order to alleviate this increasing load of high data rate applications. However, there are places where even Wi-Fi bands do not operate as expected or are found to be so congested that their use becomes next to impossible, for example, heavily crowded conference halls. Also, supported data rates of Wi-Fi as well as cellular data services should be considered in this discussion. Though IEEE 802.11ac and IEEE 802.11ad standards are supposed to support high bit rates, they are not yet widespread, and so the cost issue is involved. LTE and LTE-Advanced standards are also supposed to support high bit rates, but they use the same precious cellular
spectrum band and thus due to congestion cannot provide satisfactory performance. Hence, the pursuit of and research on alternatives to these radio frequency-based solutions such as optical wireless-based systems and technologies are greatly desirable [3, 4].

OWC can be both indoors and outdoors and are usually broadly divided into two categories based on the type of optical source employed. Two types of optical sources—LEDs and lasers—are currently in use as transmitters of optical links. The difference between these two sources lies in their supported bandwidth: where LEDs have a much lower electrical bandwidth than lasers, and hence if very high data rate transmission in the range of Gbps is required, lasers are the popular choice. Also, lasers emit monochromatic light signals, that is, light signals that have only one wavelength in it, whereas LEDs have a very broad spectral linewidth. LED-based communications mainly involve visible light communications (VLC) using white LEDs (WLEDs), and lasers are used only as very high-speed infrared sources. Hence, these two types of optical sources have different application scenarios. In this book, we will cover different types of applications where both LEDs and lasers are used.

The energy-saving aspect of WLEDs is probably one of the most important benefits that can be obtained using VLC. Lighting is a major source of electric energy consumption. It is estimated that one-third of the global consumption of electricity is spent for lighting purposes; therefore, development of more efficient lighting sources is important. This acknowledgment of concerns about significant consumption has generated significant activity toward the development of solid-state sources, to replace incandescent and fluorescent lights. Fluorescent lamps contain environmental pollutants, thus their elimination will remove a significant source of environmental pollution and more specifically, their replacement with highly efficient LEDs generating “white light” will reduce energy consumption. It is fortunate that WLEDs are already commercially available. WLEDs require roughly 20 times less power compared to conventional light sources, even 5 times less power compared to fluorescent bulbs that consume less energy. An entire rural village can be lit with less energy than that used by a single conventional 100 W light bulb. Switching to solid-state lighting would reduce global electricity use by 50% and reduce power consumption by 760 GW in the United States alone over a 20-year period. To get a clear picture of the positive impact the use of WLEDs will have, some concrete estimates can be provided. If all existing bulbs were replaced by WLED sources, within 10 years we will have the following benefits: energy savings of $1.9 \times 10^{20}$ J, US$1.83 trillion financial savings, 10.68 GT reduction of carbon dioxide emissions, and 962 million barrels less consumption of crude oil [4].

The field of photonics starts with the efficient generation of light. The generation of efficient yet highly controllable light can indeed be accomplished using LEDs. Using a WLED instead of conventional lighting means the size, cost, and energy consumption will decrease considerably, as optical devices are smaller and simpler than electrical devices. WLEDs are semiconductor devices. About 13,000 LEDs can be formed on a substrate, which can be about 0.25 × 0.25 units in size. WLEDs use 5% of the energy of a regular incandescent bulb. An entire rural village can be lit with less energy than that used by a single conventional 100 W light bulb. By replacing the conventional lights with WLEDs and by using them for both data transmission and lighting, large amounts of energy can be saved. Undoubtedly, white light emitting solid-state devices will be the lighting sources of the twenty-first century. About 10–15 years ago, researchers came to the realization that WLED devices, in addition to being very fit for lighting the surrounding space, could also be used for wireless communications purposes. The advantages of such technology applications are many. It belongs to the “green
technologies” category when used for lighting purposes, becoming even more environmentally friendly when it supports communication functionality compared to RF alternatives. Also, LEDs and photodetectors tend to be considerably cheaper compared to RF counterparts. OWC allows easy bandwidth reuse and improves security, as light is confined within the room it illuminates. It does not generate RF contamination, nor is it impacted by RF interference. Thus, replacing RF devices with devices using white light for communications (at least for indoor environments) will reduce interference in the RF bands. It should be pointed out that while the consumer market and the product developers will benefit from this, the technology can also make a major breakthrough in cases where RF radiation is of great concern, as in the case of hospitals, schools, airplanes, and mines. RF interference has caused accidental triggering of explosions when using remote detonator devices. Federal regulation places 1 W as the maximum acceptable RF power within mines using remotely triggered detonators. Also, baby monitoring RF signals have interfered with landing instructions of planes approaching airport runways.

1.1.1 Spectrum Scarcity Issues and Optical Wireless Communications as a Solution

Let us delve a bit deeper into the RF spectrum scarcity problem that we mentioned earlier and how OWC using either LEDs or lasers can help in this regard.

With the increasing popularity of multimedia services supplied over the RF networks and services such as web browsing, audio and video on demand, it is for sure only a matter of time before users will face extreme congestion while trying to connect to avail themselves of these aforementioned services. Advancements in displays, battery technology, and processing power have made it possible for users to afford and carry around smart phones and tablets. As we are entering a new era of always on connectivity, the expectation from users for not only ubiquitous but also seamless voice and video services presents a significant challenge for today’s telecommunications systems. The prospects for the delivery of such multimedia services to these users are crucially dependent on the development of low-cost physical layer delivery mechanisms.

According to market research published by Cisco Systems, Inc. [5], the largest manufacturer of networking equipment, mobile data consumption is going to explode in the next 5 years, largely due to the proliferation of mobile video and mobile web applications. Cisco market research includes the Visual Networking Index (VNI). The VNI research predicts mobile data use to expand from 2.5 to 24.3 EB monthly. This is an increase of a factor of 10 in 5 years, or about 57% cumulative annual growth rate (CAGR). This is an enormous growth in mobile data, a very large portion of which is growth due to the proliferation of mobile video (66%). Much of this mobile data growth (about 70%) will be consumed by laptops and other mobile ready portables such as pico-projectors, wireless reading devices, digital photo frames, and smart phones. These mobile devices can generally be thought of as in-building networked devices that are used to share information (video) within a classroom, conference, or meeting room. The report predicts that a greater amount of traffic will migrate from fixed to mobile networks.

In the past few years, we have witnessed rapid growth in technologies producing low-cost communications devices, using the RF license-free bands: ISM (2.4–2.4835 GHz), UNII
(5.15–5.25 and 5.35–5.825 GHz). As technology advances, the service capability of such devices will strengthen. However, uncontrolled deployment of devices using the same spectrum allocation can generate interference beyond the level that these systems can afford, thus leading to service quality deterioration. The IEEE 802.15.2 working group was formed to address this growing problem; however, without controlling the number of devices operating within certain areas, the problem cannot be solved, unless more bandwidth becomes available. The 57–64 GHz band has been added to license free bands; however, the design of communication systems at these extremely high frequencies is very challenging. It will take some years for products of reasonable cost and satisfactory performance to be introduced in the market. Also, adding bandwidth does not address the problem at its root. What is needed is a broadband, interference-free, or at least interference-resistant technology, allowing easy frequency reuse made available to the customer at an affordable cost [4]. Considering the rapidly growing wireless consumer devices, it is evident that the need for such technology is quite urgent.

The wireless handheld devices require ever-increasing bandwidth, and along with that, explosive growth in interdevice wireless communications is already creating huge demands on spectrum resources, which can be resolved only by near-zero-sum allocation decisions, made through a mixture of bidding and politics.

In economy, the game theoretic Nash equilibrium (named after John Forbes Nash, who proposed it) [6] is a solution concept of a game involving two or more players, in which each player is assumed to know the equilibrium strategies of the other players, and no player has anything to gain by changing only his own strategy unilaterally. If each player has chosen a strategy and no player can benefit by changing his or her strategy while the other players keep theirs unchanged, then the current set of strategy choices and the corresponding payoffs constitute Nash equilibrium. The practical and general implication is that when players also act in the interests of the group, then they are better off than if they acted in their individual interests alone.

Unfortunately, with spectrum usage, Nash equilibrium may result in a spectrum crunch [2], if the participants do not cooperate. An example of this was the Cellular Digital Packet Data (CDPD). This was a wide-area mobile data service, which used unused bandwidth normally used by AMPS mobile phones between 800 and 900 MHz to transfer data. Speeds up to 19.2 Kbps were possible. The service was discontinued in conjunction with the retirement of the parent AMPS service; it has been functionally replaced by faster services such as 1xRTT, EV-DO, and UMTS/HSPA. Developed in the early 1990s, CDPD was large on the horizon as a future technology. However, it had difficulty competing against existing slower but less-expensive Mobitex and DataTac systems, and never quite gained widespread acceptance before newer, faster standards such as GPRS became dominant. CDPD had very limited consumer offerings. Though AT&T Wireless first offered the technology in the United States under the PocketNet brand, they eventually refused to activate the devices. Despite its limited success as a consumer offering, CDPD was adopted in a number of enterprises and government networks. It was particularly popular as a first-generation wireless data solution for telemetry devices (machine-to-machine communications) and for public safety mobile data terminals. In 2004, major carriers in the United States announced plans to shut down CDPD service. In July 2005, the AT&T Wireless and Cingular Wireless CDPD networks were shut down. Equipment for this service now has little to no residual value [7].

Another example of co-existence with already existing services over radio spectrum (a form of bandwidth sharing) is the idea of ultra wideband (UWB) [8] that proposed to use
direct-sequence spread spectrum sharing bands over 7 GHz of already allocated radio spectrum. This technology did not go too far either, although a huge amount of resources was spent on demonstrating the feasibility of the technology through research and development. The developed technologies work perfectly according to the specifications, but there is no public acceptance in adopting these techniques.

Some views on bandwidth sharing, be it through cognitive radios or dynamic spectrum allocation (DSA) [9], are given here. The wireless/mobile environment is very dynamic. To capture when a piece of spectrum is free and available (known as white space) in order to reallocate it, many accurate energy sensors have to be installed to identify these available bands. Then a command has to be sent to a cloud (database) at a distance in order to make the availability of the idle bands known to users in order to reallocate these available bands. This is a very difficult and expensive proposition in a densely populated metropolitan area where bandwidth sharing is needed the most. There might be several available portions of bands idle in rural areas; however, bandwidth and channel borrowing concepts only work over short distances. In dense metropolitan areas, by the time sensing is done and a reallocation decision is reached, the spectrum availability status may be different.

There are many practical odds against bandwidth sharing through cooperation, and there are commercial risks involved with the results (as with CDPD). Some of these are (i) cost effectiveness of sensors and the number of sensors required; (ii) willingness of spectrum resource managers (FCC, NTIA, ITU) to allow a commercial enterprise to resell spectrum and to dynamically allocate spectrum resources; (iii) ability to raise sufficient capital to deploy a network of sensors and spectrum monitoring/allocation system in a dense geographical area; (iv) and ability to sign customers onto a plan to utilize dynamically allocated spectrum.

These are the common problems with dynamic allocation of spectrum. Regulations and protocols attempt to address these but are usually difficult to construct, and even harder to enforce. Therefore, we look for viable approaches.

We need “new spectrum,” and we also need mechanisms to address the “tragedy of the commons” problem [10] with the allocated spectrum. The tragedy of the commons is a dilemma arising from the situation in which multiple individuals, acting independently and rationally, consulting their own self-interest, will ultimately deplete a shared limited resource, even when it is clear that it is not in anyone’s long-term interest for this to happen. This dilemma was described in an influential article titled “The tragedy of the commons,” written by ecologist Garrett Hardin and first published in the Science journal in 1968 [10]. Therefore, unless some sort of regulation is implemented, the rational strategy for individual users never produces Pareto optimality among permitted users [6]. This optimality is also borrowed from game theory arguments, except that here the users have a self-policing or self-regulation imposed on them.

Self-regulation is achieved by utilizing higher frequency carriers. Higher frequency waves above 30 GHz tend to travel only a few miles or less and generally do not penetrate solid materials very well. This offers a sustainable solution for the current spectrum crunch [2]. Actually, the July, 1997 Federal Communications Commission’s Office of Engineering and Technology in USA Bulletin #70 “Millimeter Wave Propagation: Spectrum Management Implications” [11] reads thus: “The absorption bands (e.g., at 23 GHz or 60 GHz) would be applicable for high data rate systems where secure communications with low probability of intercept is desirable; for services with a potentially high density of transmitters operating in proximity; or for applications where unlicensed operations are desirable.”
To address the spectrum scarcity problem in current wireless systems, we are examining the concept of adaptive rate delivery of future mobile and portable multimedia services with high bit rates (>100 Mbps) for localized areas [4]. The motivation for operators of such bands to actually choose to self-limit is that by doing so, they improve the signal-to-noise ratio against competing users at a lower cost than trying to overcome interference. These characteristics of wave propagation are not necessarily disadvantageous as they enable more densely packed communications links. Thus, high frequencies can provide very efficient spectrum utilization through “selective spectrum reuse,” and naturally increase the security of transmissions. Hence, OWC is a direct solution in the spectrum reuse scenario.

Two branches of optical wireless have emerged contemporaneously. In one branch, semiconductor LED is considered to be the future primary lighting source for buildings, automobiles, and aircrafts. LED provides higher energy efficiency compared to incandescent and fluorescent light sources, and it will play a major role in the global reduction of carbon dioxide emissions, as a consequence of the significant energy savings. Lasers are also under investigation for similar applications. These core devices have the potential to revolutionize how we use light, including not only for illumination but also for communications, sensing, navigation, positioning, surveillance, and imaging. The second branch uses coded optical signals within two coherent optical side bands centered at different wavelengths. The two sidebands, at least one of which carries a message, are transported over long distances to a broadcast station, at which point, heterodyne interference of light within the two bands produces an electromagnetic wave at microwave or millimeter wave frequencies that is modulated by the lower frequency optically coded message. The electromagnetic wave carrying the coded message is then broadcast by an antenna. A wireless receiver can reply wirelessly over a return path via an electrically generated wave carrying an electrically generated coded message. Wired optical networks and various wireless networks are thus merged. Each of the optical wireless networks briefly described earlier has its unique applications, message coding, security features, and technology for sending and receiving messages. Among applications in this area are multiband, multi-service wireless over optical access, distributed radio-over-fiber access network for cloud-computing, broadband millimeter-wave wireless sensor communications, and microwave photonics for integrated multigigabit wireless systems.

Visible light and infrared light (IR) exhibit very similar qualitative behavior because of the closeness of their wavelengths; however, in terms of indoor communications, only IR has been used mostly until now. The reason is that until recently, it was not possible to manufacture highly efficient WLEDs. As LEDs increasingly displace incandescent lighting over the next few years, general applications of VLC technology are expected to include wireless Internet access, vehicle-to-vehicle communications, broadcast from LED signage, machine-to-machine communications, positioning systems, navigation, and so on. The VLC technology has potential in a number of specialized application areas including the following: (i) Indoors/Outdoors Light Positioning System (LPS) in analogy to GPS; (ii) Light Navigation Systems; (iii) Hospital and Healthcare—enabling mobility and data communications in hospitals; (iv) Hazardous Environments—enabling data communications in environments where RF might be potentially harmful (i.e., Oil and Gas, Petrochemicals and Mining); (v) Commercial Aviation—enabling wireless data communications such as in-flight entertainment and personal communications; (vi) Corporate and Organizational Security—enabling the use of Wireless Networks in applications where Wi-Fi presents a security risk; (vii) Wi-Fi Spectrum
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Relief—providing additional bandwidth in environments where unlicensed communication bands are congested; (viii) Defense and Military Applications—enabling high data rate wireless communications within military vehicles and aircrafts; (ix) Underwater communications—between divers and/or remote-operated vehicles.

Examples of localized areas could be classrooms, hotel rooms, future homes, shopping malls, waiting rooms in airports and train stations, planes, space-crafts, and so on. Consider the area of home networking—when in the very near future, every home will be illuminated with bright visible LED lights, they can also be used as a broadband communications carrier. Light-waves at visible and IR wavelength range and beyond are confined to the walls in a room and generally do not penetrate solid materials. Hence, practical and usable networks can be readily realized, which utilize this self-limiting link distance. We call such systems high-bandwidth islands that employ this property. The motivation for operators to actually choose to transfer data through this optical band is that by doing so, the entire huge bandwidth can be reused next door, free of interference.

In large open environments where individual users may require 100 Mbps speed or more, optical wireless (OW) is a more sensible solution because of its limited cell size. Today’s RF LANs realistically cannot support more than a couple of high capacity users per cell, which is highly wasteful. Multiple high-capacity users require multiple cells and thus create a situation where the cells almost completely overlap, which then raises concerns with regard to interference, carrier reuse, and so on. In contrast, OW could deliver the necessary capacity to each user through multiple user-sized cells, and because of the intrinsically abrupt boundary of these cells, interference would be negligible and carrier reuse would not be an issue. These cells, or high-bandwidth islands, can indeed solve much of the spectrum shortage problem by transferring the high-bandwidth multimedia payloads to wireless optical carriers from radio frequency. Also OW is a future proof solution, as additional capacity far beyond the capabilities of radio could be delivered to users as their needs increase with time.

VLC could be a viable option for optical wireless systems as LEDs can be used as a wireless communications transmitter. This is not possible for any other kind of lamps in broadband transmissions. One can use the same visible light LEDs not only for lighting homes but also as light sources for wireless in-house communications [12], and there is now an IEEE standards committee addressing the issues of this application. A full duplex operation thus can be realized by using IR as uplink and visible light LEDs as downlink. Using this new and developing technology along with power-line communications (PLC) and smart-grid can go a long way to mitigate the spectrum crunch problem as there will no longer be a need for separate lighting and communications equipment or interference creating RF restrictions.

It is commonly agreed that future generations of wireless communications systems will not be based on a single access technique but will encompass a number of different complementary access technologies. Surprisingly, currently perhaps the largest installed base of short-range wireless communications links are optical, rather than RF. Indeed, “point and shoot” links corresponding to the Infra-Red Data Association (IRDA) standards are installed in 100 million devices a year, mainly remote controls. It is argued that OW has an important part to play in the wider 5G vision as the communications technology of the future. Thus it is high time that multimedia transmissions requiring high-bandwidth in indoors be shifted to optical bands as an effective strategy to overcome the spectrum shortage problem.
1.2 Organization

In Chapter 2, we discuss some fundamentals of OWC systems. There are differences between radio frequency-based and OWC systems that we provide details on. We also discuss optical transmitters and receivers.

The goal of Chapter 3 is to establish a proper channel modeling method to ensure that modeling can be done accurately and fast. Channel modeling is very important for optical wireless links as optical signals bounce back and forth from the walls within a room and hence the receiver receives delayed or reflected versions of the same signal. As this is the cause of intersymbol interference (ISI) at high data rates, modeling the channel to better understand this multipath phenomenon is an important topic.

Our objective in Chapter 4 is to analyze various channel properties using the models obtained from channel modeling techniques. We discuss different topics related to indoor optical wireless channels such as root mean square delay spread and path loss. We see the effects of additional room furniture on these parameters also compared to an empty room.

Chapter 5 consists of several fundamental researches on multiple sources VLC. Source layout is one of the most important factors that affect overlapping of light footprints and thus produce ISI. It determines the pattern and extent of the overlapped lights. We explore VLC performance in conventional household layouts and investigate the impact of these layouts on VLC.

Orthogonal frequency division multiplexing (OFDM) is currently being used predominantly in RF mobile broadband communication systems because of its ability to combat ISI and robustness against frequency-selective fading caused by multipath wireless channel. OFDM is also being considered as a candidate for VLC as it offers robustness against multipath, caused by diffuse indoor OW channel. However, OFDM suffers from certain disadvantages such as high peak-to-average power ratio (PAPR). Also, optical wireless transmissions require the modulating signal to be unipolar. In Chapter 6, we develop some techniques to reduce high PAPR in OFDM-based OW systems as the nonlinear characteristics of LED transmitters can severely affect system performance. We look into various precoding-based PAPR reduction techniques. We then analyze performance of various OFDM-based OW schemes in multipath diffuse indoor wireless channels. We compare the performance of conventional schemes with a precoded version.

In Chapter 7, multiple-input and multiple-output (MIMO) techniques are included as they provide either reliability improvement or bandwidth efficiency increase. Based on these investigations, we further explore VLC performance in real applications, such as aircraft cabin wireless communications in Chapter 8.

In Chapter 9, we discuss multispot diffusing configuration where multiple spots on the ceiling of a room are created with the help of a holographic diffuser. We also discuss angle-diversity receivers that are set up in such a way that several photodiodes are arranged at different angles relative to each other and thus face different directions, or can be constructed using holographic mirrors.

In Chapter 10, we discuss an important application of VLC-based OWC techniques—indoor positioning and navigation systems. Indoor positioning has become an attractive research topic in the past two decades. However, no satisfying solution has been found with consideration to both accuracy and system complexity. Recently, research on visible light communications has offered new opportunities in realizing accurate indoor positioning with
relatively simple system configurations. In this chapter, we also investigate several fundamental research topics of indoor positioning systems based on VLC technology.

References
