1 Introduction

Shlomi Arnon

Visible light communications (VLC) is the name given to an optical wireless communication system that carries information by modulating light in the visible spectrum (400–700 nm) that is principally used for illumination [1–3]. The communications signal is encoded on top of the illumination light. Interest in VLC has grown rapidly with the growth of high power light emitting diodes (LEDs) in the visible spectrum. The motivation to use the illumination light for communication is to save energy by exploiting the illumination to carry information and, at the same time, to use technology that is "green" in comparison to radio frequency (RF) technology, while using the existing infrastructure of the lighting system. The necessity to develop an additional wireless communication technology is the result of the almost exponential growth in the demand for high-speed wireless connectivity. Emerging applications that use VLC include: a) indoor communication where it augments WiFi and cellular wireless communications [4] which follow the smart city concept [5]; b) communication wireless links for the internet of things (IOT) [6]; c) communication systems as part of intelligent transport systems (ITS) [7–14]; d) wireless communication systems in hospitals [15–17]; e) toys and theme park entertainment [18, 19]; and f) provision of dynamic advertising information through a smart phone camera [20].

VLC to augment WiFi and cellular wireless communication in indoor applications has become a necessity, with the result that many people carry more than one wireless device at any time, for example a smart phone, tablet, smart watch, and smart glasses and a wearable computer, and at the same time the required data rate from each device is growing exponentially. It is also becoming increasingly clear that in urban surroundings, human beings spend most of their time indoors, so the practicality of VLC technology is self-evident. It would be extremely easy to add extra capacity to existing infrastructure by installing a VLC system in offices or residential premises. In Fig. 1.1 we can see an example of a VLC network that provides wireless communication to a laptop, smart phone, TV, and wearable computer.

The downlink includes illumination LED, Ethernet power line communication (PLC) modem, and LED driver, which receives a signal by a dedicated or dongle receiver as part of the device. The uplink configuration could be based for example on: a) a WiFi link; b) an infrared–IRDA link; or c) a modulated retro reflector (Fig. 1.2). A modulated retro reflector is an optical device that retro reflects incident light [21, 22]. The amplitude of the retro reflected light is controlled by an electronic signal, as a result modulation of the light can be achieved. In the cases of an infrared–IRDA [23] link or a modulated retro reflector

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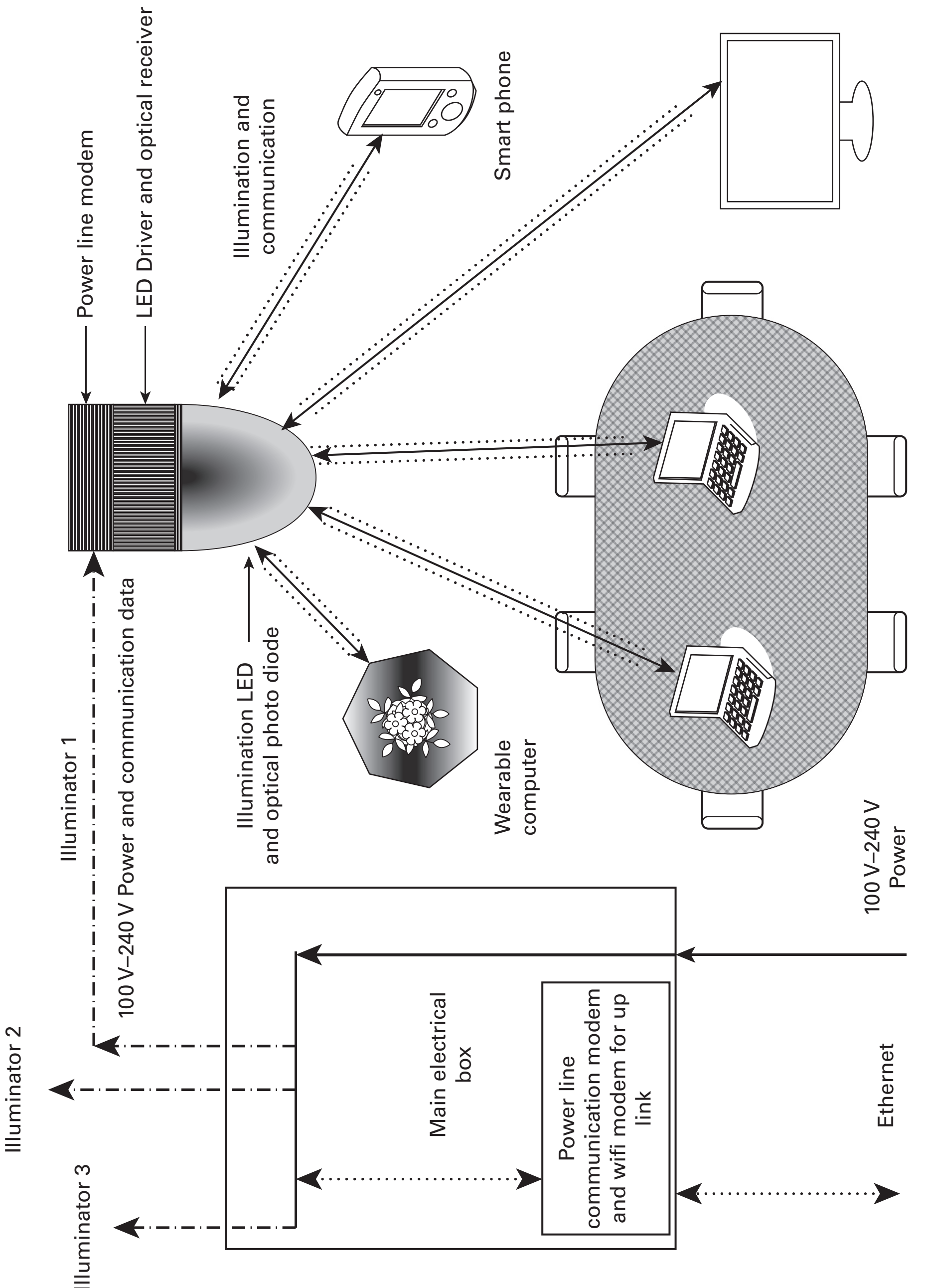

Figure 1.1 VLC wireless network.

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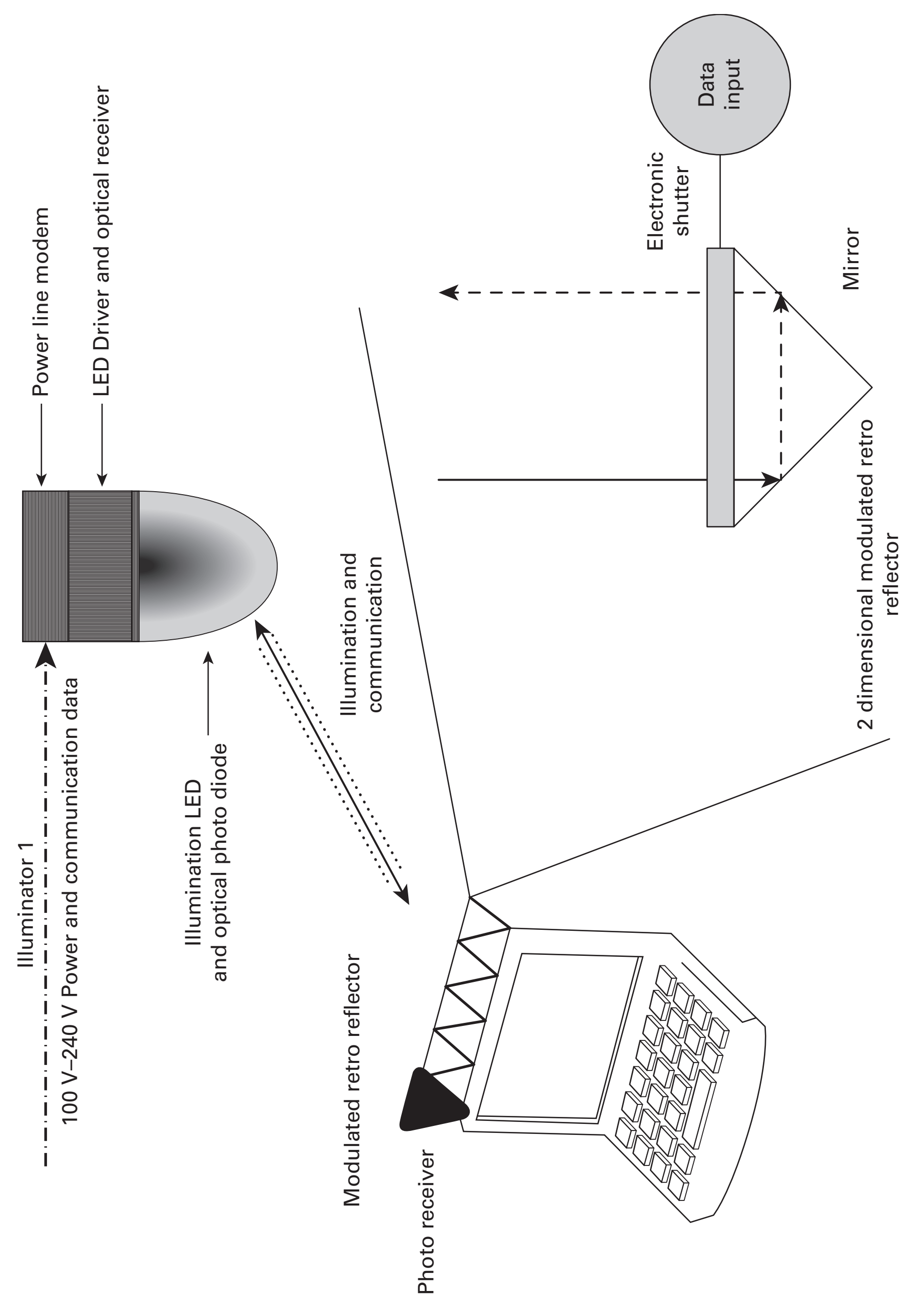

Figure 1.2 A wireless communication network based on modulated retro reflector.

the receiver could be part of the illumination LED. In that case the uplink receiver includes photo diode, trans impedance amplifier and modem. In this way, an operational wireless network could be created in next to no time.

In the near future, billions of appliances, sensors and instruments will have wireless connectivity, as can be anticipated from the revolutionary concept of the internet of things (IOT). This technology makes it possible to have ambient intelligence and autonomous control which could adapt the environment to the requirements and the desires of people. VLC could be a very relevant wireless communication technology that is cheap, simple and immediate and does not encroach on an already crowded part of the electromagnetic spectrum.

Intelligent transport systems (ITS) are an emerging technology for increasing road safety and reducing the number of road casualties as well as for improving traffic efficiency (Fig. 1.3). VLC have been proposed as a means for providing inter-vehicular communication and for establishing connectivity between vehicular and road infrastructure, such as traffic lights and billboards. These systems provide one-way or two-way short- to medium-range wireless communication links that are specifically designed for the automotive sphere. The technology uses the headlights and the rear lights of cars as transmitters, and cameras and detectors as the receivers. The traffic lights are the counterpart of a transmitter in this sphere.

The medical community pursues ways to improve the efficiency of hospitals and at the same time to reduce hospital-acquired infections, which are very costly in money and human life. One way to upgrade the communication infrastructure is by wireless technology. The technology makes it possible for doctors to access and update patient data using tablet computers at the patient's bedside instead of manually keeping paper

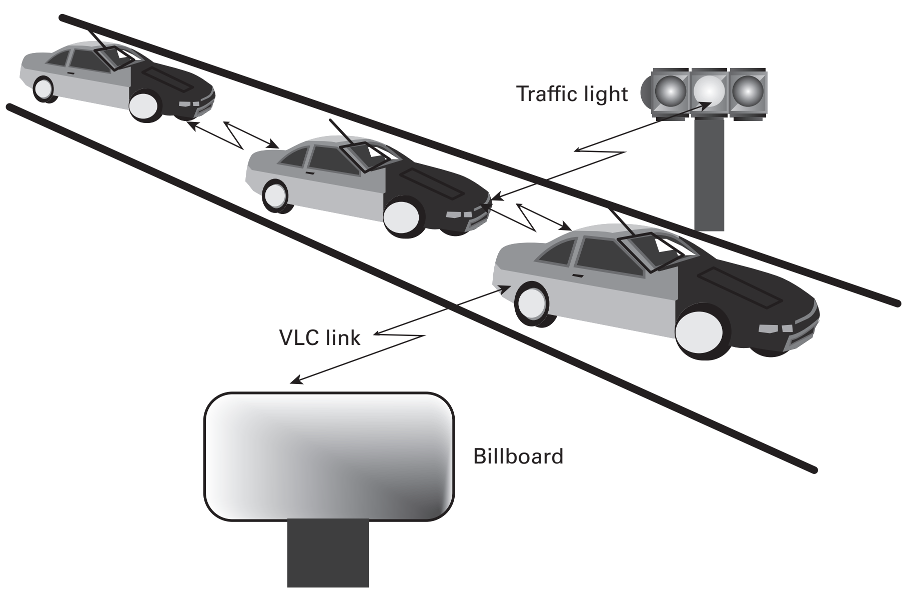

Figure 1.3 An intelligent transport system using VLC.

documents that are kept either at the bedside or in the nurses' back office station. Another application is a device used to monitor patient well-being and vital data remotely. Due to the fact that RF, like WiFi and cellular, is a best effort technology, meaning that the transmission of information is not guaranteed, interference from nearby devices could jam the communication. This situation is unacceptable for medical applications and therefore a switch to VLC technology is self-evident. It is clear that VLC technology can provide localized solutions immune to interference and jamming for the medical domain.

The toys and theme park entertainment sector is a very interesting application that takes advantage of VLC technology due to two main characteristics (Fig. 1.4). The first characteristic is the ability to communicate by line of sight or semi line of sight, so the communication is localized to a specific volume. This makes it possible to provide location based information in the theme park so the audience will have a multi-dimensional and multi-sensory experience. The same concept could be used in the toys market to communicate between toys, using the already present LED. The second characteristic is the low cost required to implement the technology in toy and park

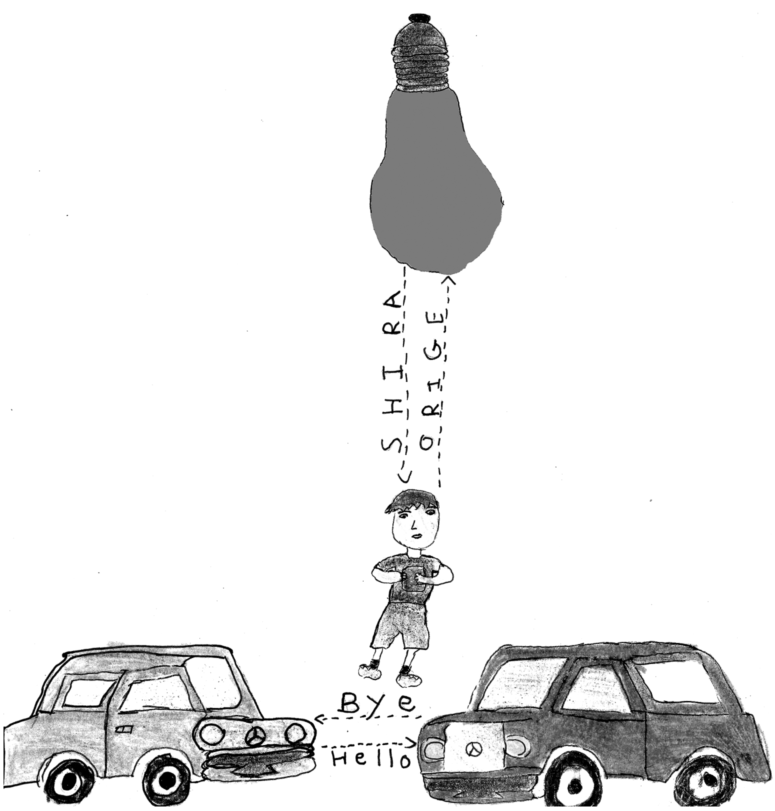

Figure 1.4 VLC in toys in the theme park entertainment industry (courtesy of S. Arnon).

entertainment. One example of a way to reduce the cost of toys is using the toy LED simultaneously as transmitter and photo diode receiver.

Dynamic advertising through a smart phone camera is a new area that uses a billboard and illumination to transmit information that is detected by the camera, and then by an appropriate algorithm the communications data are extracted from the video. This technology could be used to add an extra and dynamic layer of information to advertisements in the street, shopping center and subway.

The IEEE has defined a new standard, IEEE 802.15.7, which describes high data rate VLC, up to 96 Mb/s, by fast modulation of optical light sources. Meanwhile, in several experiments around the world data rates of more than 500 Mb/s have been reported [24–27]. In addition many new methods are being developed to maximize bit rates and to provide algorithms to manage interference and subcarrier re-use [27–33], methods to analyze synchronization issues [34] and methods to design an asymmetric communication system using modulated retro-reflectors (MRR) based on nanotechnology [35]. In the light of these developments a new methodological book covering this subject is required in order to help progress the technology. The aspiration of this book is to serve as a textbook for undergraduate and graduate level courses for students in electrical engineering, electro-optical engineering, communications engineering, illumination engineering and physics. It is also intended to serve as a source for self-study and as a reference book for senior engineers involved in the design of VLC systems.

The book includes nine chapters that cover the important aspects of VLC scientific theory and technology. Following this introductory chapter, Chapter 2 deals with modulation techniques under lighting constraints, and is written by Jae Kyun Kwon and Sang Hyun Lee. The authors explain that the physical layer design of VLC systems is of substantially different character than conventional wireless systems, notably with regard to a new average intensity constraint. This new constraint, which will be referred to as the "dimming target" of the illumination system, introduces a new domain of system design that has rarely been considered in existing communication media. Chapter 3, by Wen-De Zhong and Zixiong Wang, describes methods such as receiver plane tilting and a special LED lamp arrangement as performance enhancement techniques for indoor VLC systems. The next two chapters, 4 and 5, deal with very important aspects of VLC, which take advantage of the characteristics of light to obtain location information. Chapter 4, by Mohsen Kavehrad and Weizhi Zhang, outlines the applications, investigates current access to the radio spectrum and studies in depth the shifting needs of indoor positioning in the visible light spectrum. At the end of the chapter, challenges and potential solutions are discussed. Chapter 5, by Zhengyuan Xu, Chen Gong, and Bo Bai, presents indoor and outdoor light positioning systems (LPS). For indoor LPS, combining VLC with position estimation methods is presented and an optimal estimation algorithm is implemented at the receiver to provide an unbiased estimate of the camera position. For outdoor automotive LPS, the light signal could be emitted from a traffic light, carrying its position information. Then, the position of the vehicle could be estimated based on the received position information of the traffic light and the time difference of arrival (TDoA) of the light signal at two photodiodes. Chapter 6, by Kang Tae-Gyu describes the standards for VLC. In this chapter, the lamp and electronic power are presented in terms of electric safety in IEC TC 34. Later, other standards for VLC, such as PLASA E1.45 and IEEE 802.15.7, which need a number of protocols between a sending party and a receiving party are discussed, as well as electric safety. This chapter also discusses the compatibilities of the VLC service area, illumination, vendor considerations and standards. Chapter 7, by Shlomi Arnon, presents different modulation methods used in VLC, such as on off keying (OOK) pulse position modulation (PPM), inverse pulse position modulation (IPPM) and variable pulse position modulation (VPPM). Later, explanations are given on how to calculate the bit error rate (BER) for each modulation scheme. A detailed description of how to calculate the effect of synchronization time offset and clock jitter on the BER performance is also presented. Chapter 8, by Klaus-Dieter Langer, describes discrete multitone (DMT) modulation for VLC and presents advanced and highly spectrally efficient solutions for this scheme, such as DC-biased DMT, asymmetrically clipped optical OFDM (ACO-OFDM) and pulse-amplitude-modulated discrete multitone (PAM-DMT). Chapter 9, by Shinichiro Haruyama and Takaya Yamazato, deals with image sensor based VLC and introduces two unique applications using an image sensor: (1) massively parallel visible light transmissions that can theoretically achieve a maximum data rate of 1.28 Gigabits per second; and (2) accurate sensor position estimation that cannot be realized by a VLC system using a single-element photodiode (PD). Applications of image sensor based communication for the automotive industry, position measurements in civil engineering and bridge position monitoring are also presented.

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2 Modulation techniques with lighting constraints

Jae Kyun Kwon and Sang Hyun Lee

The physical layer design of visible light communication (VLC) systems is of substantially different characteristics from standard RF communications in that it involves a new constraint, namely a lighting constraint. This kind of constraint is imposed on the average intensity and flicker of the light emission. Since the flicker has little impact on human eye perception when light pulses blink at 200 Hz or higher frequency, the average intensity constraint is mainly addressed in this chapter. While this constraint is usually given as an inequality in optical wireless communication, it is represented as an equality in VLC. In addition, compared to radio-frequency communication, where the signal power, the squared value of signal level, is usually constrained, the intensity, the signal level itself, is constrained. In other words, the lighting constraint is defined with respect to the average (the first-order moment) of the signal, instead of the variance (the second-order moment). Therefore, this new constraint, which will be referred to as the dimming target, introduces a new domain of system design which has rarely been considered in existing communication media.

In this chapter, several ways of communicating a message subject to the average constraint are addressed. This chapter is far from comprehensive but attempts to offer several promising ways of achieving such a goal. To satisfy the lighting constraint represented by the average constraint, several approaches have been addressed, and they can be categorized as to shift signal levels, to compensate in time, and to change level distribution. Some of those schemes are simply realized, and some provide improved throughput. First, the shift of the signal level is one of the simplest approaches. A typical non-return-to-zero (NRZ) on-off keying (OOK) has 50% average intensity for uniform probability of binary symbols. For the lighting constraint of 75% dimming, it offers a simple solution of moving the OFF symbol level from 0% intensity to 50%, which is referred to as analog dimming. Although this is conceptually simple, a non-linear characteristic of LEDs poses some technical difficulties, and the reduced level spacing degrades detection performance.

Second, compensation of the intensity difference in time is another approach that can be simply realized. For general data transmission with 50% average intensity, i.e., uniform symbol probability, when the lighting constraint of 75% dimming is targeted, the same duration of *dummy* ON transmission time as the data transmission time is appended to meet the target. If the target is below 50%, a dummy OFF symbol interval is applied to resolve the difference. Those dummy transmissions may be either appended after each

