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Part I

Outlook

1 Introduction

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Optical wireless communication is an emerging and dynamic research and development area that has generated a vast number of interesting solutions to very complicated communication challenges. For example, high data rate, high capacity and minimum interference links for short-range communication for inter-building communication, computer-to-computer communication, or sensor networks. At the opposite extreme is a long-range link in the order of millions of kilometers in the new mission to Mars and other solar system planets. It is important to mention that optical wireless communication is one of the oldest methods that humanity has used for communication. In prehistoric times humans used fire and smoke to communicate; later in history, Roman optical heliographs and Sumerians signalling towers were the communication systems of these empires. An analogous technology was used by Napoleonic Signalling Towers and "recently" by the light photo-phone of Alexander Graham Bell back in the 1880s.

Obviously, the data rate, quality of service delivered, and transceiver technologies employed have improved greatly from those early optical wireless technologies. In its many applications, optical wireless communication links have already succeeded in becoming part of our everyday lives at our homes and offices. Optical wireless products are already well familiar, ranging from visible-light communication (VLC), TV remote control to IrDA ports that currently have a worldwide installed base of hundreds of million of units with tens of percent annual growth. Optical wireless is also widely available on personal computers, peripherals, embedded systems and devices of all types, terrestrial and in-building optical wireless LANs, network of sensors, and inter-satellite link applications.

The book includes three main parts: Part II Optical wireless communication theory, Part III Unique channels, and Part IV Applications.

Part II describes important issues in optical wireless theory starting with Chapter 2 about coding and modulation techniques for optical wireless channels by Ivan B. Djordjevic. The author explains that the communication over the FSO channel is achieved through the line-of-sight (LOS) between two distant transceivers. An optical wave propagating over the FSO channel experiences fluctuations in amplitude and phase due to atmospheric turbulence, which represents a fundamental problem present even under clear sky conditions. In this chapter, several coded modulation concepts

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enabling communication over strong atmospheric turbulence channels are described: (i) coded-multiple-input multiple-output (MIMO), (ii) raptor coding, (iii) adaptive modulation and coding (AMC), (iv) multidimensional coded modulation, and (v) coded-orthogonal frequency division multiplexing (OFDM). Furthermore, the concept of heterogeneous optical networking is discussed. Chapter 3 titled "Wireless optical CDMA communication systems" by Jawad A. Salehi, Babak M. Ghaffari, and Mehdi D. Matinfar, describes a particular and advanced form of optical wireless communication systems, namely optical code-division multiple-access (OCDMA), in the context of wireless optical systems. As wireless optical communication systems gets more mature and become viable for multi-user communication systems, advanced multiple-access techniques become more important and attractive in such systems. Among all multiple-access techniques in optical domain, OCDMA is of utmost interest because of its flexibility, ease of implementation, no need for synchronization among many users and soft traffic handling capability. The deployment of OCDMA communication systems in both indoor and outdoor free-space optical links is also analyzed. Chapter 4 is "Pointing error statistics" by Shlomi Arnon. In this chapter the author presents a simple model that describes the effect of the statistic of the pointing error on the performance of communication systems. Chapter 5 is "Equalization and Markov chains in cloud channel" by M. Kavehrad. The focus of this chapter is on investigating the possibility of simplifying the task of calculating the performances in cloud channel by a direct extraction of state transition matrices associated with standard Markov modeling from the MCRT computer simulations programs. Chapter 6 by Steve Hranilovic considers multiple-input multiple-output (MIMO) techniques employing a number of optical sources as transmitters and a collection of photodiodes as receivers for indoor optical wireless (OW) channels. The OW MIMO systems discussed in this chapter differ fundamentally from those used in radio channels. In particular, the signalling constraints imposed by intensity-modulated/direct-detection (IM/DD) systems limit the direct application of theory from radio channels. Nonetheless, MIMO techniques can be applied to OW channels to yield improvements in reliability and to improve data rates. This chapter starts with a brief overview of the characteristics of indoor OW MIMO systems. Given that the application and available gains depend on channel architecture, the balance of the chapter considers the use of MIMO techniques in three main OW channel topologies: diffuse, spot-diffusing, and point-to-point. The last chapter in this part, Chapter 7 by Amos Lapidoth, Stefan M. Moser, Michèle Wigger, describes the basics of channel capacity. In this chapter the authors focus on communication systems that employ pulse amplitude modulation (PAM), which in the case of optical communication is called pulse intensity modulation. In such systems the transmitter modulates the information bits onto continuous-time pulses of duration T, and the receiver preprocesses the incoming continuous-time signal by integrating it over nonoverlapping intervals of length T. Such continuous-time systems can be modeled as discrete-time channels where the (discrete) time k input and output correspond to the integrals of the continuous-time transmitted and received signals (i.e., optical intensities) from kT to $(k+1)T$. Note that for such discrete-time systems, the achieved data rate is not measured in bits (or nats) per second, but in bits (or nats) per channel use. They discuss three different discrete-time, pulse intensity modulated, optical channel models: the discrete-time Poisson channel, the free-space optical intensity channel, and the optical intensity channel with input-dependent Gaussian noise.

Part III describes unique channels that could be found in optical wireless applications. Chapter 8: "Modeling and characterization of wireless ultraviolet scattering communication channels" by Zhengyuan Xu, Brian M. Sadler, Gang Chen, and Haipeng Ding, describes the modeling and characterization issues that arise from short-range communications over non-line-of-sight (NLOS) ultraviolet (UV) atmospheric scattering channels. The chapter starts by presenting the unique channel properties and history of NLOS UV communications, and introducing outdoor NLOS UV scattering link geometries. Both single and multiple scattering effects are considered, including channel impulse response and link path loss. Analysis and Monte Carlo simulation are employed to investigate the UV channel properties. The authors also report on experimental outdoor channel measurements, and compare with theoretical predictions. Chapter 9 titled "Free space optical communications underwater" by Brandon Cochenour and Linda Mullen, serves as both an introduction to the field of light propagation underwater, as well as a survey of current literature pertaining to underwater free-space optics (uFSO) or underwater optical wireless communication. The authors begin with a simple examination of a link budget equation. Next, they present an introduction of ocean optics in order to gain an appreciation for the challenges involved with implementing free-space optical links underwater. They then discuss state-of-the-art theoretical and experimental methods for predicting beam propagation in seawater. Finally, they present some common uFSO link types, and discuss the system-level design issues associated with each. Chapter 10 by Roger Green and Mark Leeson deals with Indoor IR communication channel. Infrared (IR) indoor optical wireless (OW) potentially combines the high bandwidth availability of optical communications with the mobility found in radio frequency (RF) wireless communication systems. So although IR is currently overshadowed by a multitude of home and office RF wireless networking schemes, it has significant potential when bandwidth demand is high. Compared to an RF system, OW offers the advantageous opportunity for high-speed medium- to short-range communications operating within a virtually unlimited and unregulated bandwidth spectrum using lower-cost components. Thus, the first sections of the chapter provide a brief overview of the system configurations, sources, detectors and filters used for OW followed by consideration of bit error rate (BER) performance in typical indoor scenarios. The third chapter in this part, Chapter 11, describes the concept of hybrid RF/optical wireless systems channel. The authors of this chapter are Nick Letzepis and Albert G. i Fàbregas. The authors remind us that in free-space optical (FSO) communication an optical carrier is employed to convey information wirelessly. FSO systems have the potential to provide fiber-like data rates with the advantages of quick deployment times, high security, and no frequency regulations. Unfortunately such links are highly susceptible to atmospheric effects. Scintillation induced by atmospheric turbulence causes random fluctuations in the received irradiance of the optical laser beam. Numerous studies have shown that performance degradation caused by scintillation can be significantly reduced through the use of multiple-lasers and multiple-apertures, creating the well-known multiple-input multiple-output (MIMO) channel. However, it is the large attenuating effects of cloud and fog that pose the most formidable challenge. Extreme low-visibility fog can cause signal attenuation on the order of hundreds of decibels per kilometre. One method to improve the reliability in these circumstances is to introduce a radio frequency (RF) link to create a hybrid FSO/RF communication system. When the FSO link is blocked by cloud or fog, the RF link maintains reliable communications, albeit at a reduced data rate. Typically a millimetre wavelength carrier is selected for the RF link to achieve data rates comparable to that of the FSO link. At these wavelengths, the RF link is also subject to atmospheric effects, including rain and scintillation, but less affected by fog. The two channels are therefore complementary: the FSO signal is severely attenuated by fog, whereas the RF signal is not; and the RF signal is severely attenuated by rain, whereas the FSO is not. Both, however, are affected by scintillation. They propose a channel model for hybrid FSO/RF communications based on the well-known parallel channel, that takes into account the differences in signaling rate, and the atmospheric fading effects present in both the FSO and RF links. These fading effects are slow compared to typical data rates and, as such, each channel is based on a block-fading channel mode.

Part IV covers applications based on optical wireless communication. It begins with Chapter 12 about quantum encryption by Rupert Ursin, Nathan Langford, and Andreas Poppe. In this chapter the authors explain that the ability to guarantee security and privacy in communication are critical factors in encouraging people to accept and trust new tools and methods for today's information-based society (e.g. eCommerce, eHealth) and for future services (e.g. eGovernment, eVoting). The trend towards faster electronics provides the ability to handle longer keys, thus providing better security, but also increases the possibility of breaking keys in state-of-the-art cryptosystems. Nevertheless modern quantum cryptography has created a new paradigm for cryptographic communication, which provides strong security and incontrovertible evidence of any attempted eavesdropping which is based on theoretically and experimentally proven laws of nature. This technique, called quantum key distribution (QKD), generates a symmetrical classical bit string using the correlations of measurements on quantum systems and has already developed into a mature technology providing products capable of everyday use. The main hurdle for quantum communication is that, with present fiber and detector technologies, terrestrial QKD links are limited to distances of just over 100 km, well within reach of how far someone could travel in a short time to simply deliver the information in person. In the future, however, it will be possible to extend the distances spanned by individual fiber-based QKD links by using repeater nodes. These individual QKD links could then be combined to create larger and more complex QKD networks which will allow many different combinations of users to be connected over the same infrastructure. The economic benefits of such an interlinking network approach to QKD will be most apparent in a typical metropolitan scenario, where many potential users are likely to be located in a relatively small area, each wanting to be able to communicate securely with many different partners. Chapter 13 covers modulating retro-reflectors by William Rabinovich. In this chapter the author make it clear that direct FSO links with active terminals on both ends have many good applications. There are, however, other applications in which the two ends of the link have different payload and power capabilities. Some examples include: unattended sensors, small unmanned aerial vehicles (UAVs) and small, tele-operated robots. For these applications a modulating retro-reflector (MRR) may be an appropriate solution. The MRR imposes a modulation on the interrogating beam and passively retro-reflects it back to the interrogator. The passive retro-reflector will generally have a large field of view over which incident light will be reflected back to its source, thus eliminating, or greatly reducing, pointing requirements on this end of the link. Despite this, the retro-reflected beam divergence can be very small, preserving the desirable features of direct FSO such as security and non-interference. Chapter 14 by Kang Tae-Gyu describes the emerging technology of visible-light communication. Visible-light communications is the name given to a wireless communication system that conveys information by modulating light that is visible to the human eye. Communications may not be the primary purpose of the light; in many applications the light primarily serves as a source of illumination. Interest in VLC has grown rapidly with the growth of visible-light light emitting diodes (LEDs) for illumination. The motivation is clear: When a room is illuminated by LEDs, why not exploit it to provide communications as well as illumination? This sharing of resources can save electric power and raw materials.

Chapter 15 targets the area of sensor networks and is written by Dominic C. O'Brien and Sashigaran Sivathasan In this chapter two architectures that use retro-reflectors are described, based on the use of retro-reflecting links for sensor network application. In the first optical links provide all the communications of the system, and in the second this is augmented by the use of short-range RF links. These are given as representative examples only, and are not meant to represent any "best" approach to using optical wireless in sensor networks. However, they do illustrate some of the challenges and potential advantages of using this technique.

The combination of the different chapters within the book provides a unique database and a wide base of knowledge. The aspiration is to serve as a textbook for a graduate-level course for students in electrical engineering, electro optics engineering, communication engineering, and physics. It is also intend to serve as a source for self-study and as a reference book for senior engineers involved in the design of wireless communication systems. The background required for this book includes good knowledge in the areas of generating and detection of optical signal, probability and stochastic process, and communication theory. Part of this information and additional reading could be found in the books: *Applied Aspects of Optical Communication and LIDAR* by N. Blaunstein, S. Arnon, N. Kopeika, A. Zilberman, and *Optical Communication* Second Edition, by R. Gagliardi and S. Karp; and in the optical wireless communication special issues in *OSA/JON* 2006 and *IEEE /JSAC* 2009.

Part II

Optical wireless communication theory

2 Coded modulation techniques for optical wireless channels

Ivan B. Djordjevic

The transport capabilities of optical communication systems have increased tremendously in the past two decades, primarily due to advances in optical devices and technologies, and have enabled the Internet as we know it today with all its impacts on the modern society. Future internet technologies should be able to support a wide range of services containing a large amount of multimedia over different network types at high transmission speeds. The future optical networks should allow the interoperability of radio frequency (RF), fiber-optic and free-space optical (FSO) technologies. However, the incompatibility of RF/microwave and fiber-optics technologies is an important limiting factor in efforts to further increase future transport capabilities of such hybrid networks. Because of its flexibility, FSO communication is a technology that can potentially solve the incompatibility problems between RF and optical technologies. Moreover, FSO technologies can address any type of connectivity needs in optical networks. To elaborate, in metropolitan area networks (MANs), FSO communications can be used to extend the existing MAN rings; in enterprise networks, FSO can be used to enable local area network (LAN)-to-LAN connectivity and intercampus connectivity; and, last but not the least, FSO is an excellent candidate for the last-mile connectivity. FSO links are considered as a viable solution for various applications listed above because of the following properties [1]–[15]: (i) the high-directivity of the optical beam provides high power efficiency and spatial isolation from other potential interferers, a property not inherent in RF/microwave communications, (ii) FSO transmission is unlicensed, (iii) the large fractional-bandwidth coupled with high optical gain using moderate powers permits very high data rate transmission, (iv) the state-of-the-art fiber-optics communications employ intensity modulation with direct detection (IM/DD), and the components for IM/DD are widely available, and (v) FSO links are relatively easy to install and easily accessible for repositioning when necessary.

The communication over the FSO channel is achieved through the line-of-sight (LOS) between two distant transceivers. An optical wave propagating over the FSO channel experiences fluctuations in amplitude and phase due to atmospheric turbulence, which represents a fundamental problem present even under clear sky conditions. In this chapter, we describe several coded modulation concepts enabling communication over strong atmospheric turbulence channels: (i) coded-multiple-input multiple-output

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(MIMO), (ii) raptor coding, (iii) adaptive modulation and coding (AMC), (iv) multidimensional coded modulation, and (v) coded-orthogonal frequency division multiplexing (OFDM). We also discuss the concept of heterogeneous optical networking. This chapter is organized as follows. The FSO channel model is introduced in Section 2.1. The codes on graphs suitable for use in FSO communications are described in Section 2.2. The concept of coded-MIMO is introduced in Section 2.3. The raptor coding concept for temporally correlated FSO channels is described in Section 2.4. The AMC concept is introduced in Section 2.5. We consider both feed-back AMC and hybrid FSO-RF communication scenarios. The multidimensional coded modulation concept is introduced in Section 2.6. The concept of FSO-OFDM transmission is introduced in Section 2.7. The heterogeneous optical networking concept is introduced in Section 2.8. Finally, Section 2.9 summarizes this chapter.

2.1 Atmospheric turbulence channel modeling

A commonly used turbulence model assumes that the variations of the medium can be understood as individual cells of air or eddies of different diameters and refractive indices. In the context of geometrical optics, these eddies may be observed as lenses that randomly refract the optical wavefront, generating a distorted intensity profile at the receiver of a communication system. The intensity fluctuation is known as scintillation, and represents one of the most important factors that limit the performance of an atmospheric FSO communication link. The most widely accepted theory of turbulence is due to Kolmogorov [1]. This theory assumes that kinetic energy from large turbulent eddies, characterized by the parameter known as outer scale L_0, is transferred without loss to the eddies of decreasing size down to sizes of a few millimeters characterized by the inner scale parameter l_0. The inner scale represents the cell size at which energy is dissipated by viscosity. The refractive index varies randomly across the different turbulent eddies and causes phase and amplitude variations to the wavefront. Turbulence can also cause the random drifts of optical beams – a phenomenon usually referred to as wandering – and can induce beam focusing.

The outer scale is assumed to be infinite in this chapter. Understanding the turbulence effects under zero inner scale is important as it represents a physical bound for the optical atmospheric channel and as such it has been of interest to researchers [1]. To account for the strength of turbulence we use the unitless Rytov variance, given by [1]

$$\sigma_R^2 = 1.23\, C_n^2\, k^{7/6} L^{11/6}, \tag{2.1}$$

where $k = 2\pi/\lambda$ is the wave number, λ is the wavelength, L is the propagation distance, and C_n^2 denotes the refractive index structure parameter, which is constant for horizontal paths. Weak fluctuations are associated with $\sigma_R^2 < 1$, strong fluctuations with $\sigma_R^2 > 1$, and the saturation regime is defined by $\sigma_R^2 \to \infty$ [1].

To characterize the FSO channel from a communication theory point of view, it is useful to give a statistical representation of scintillation. The reliability of a communication link can be determined if we use a good probabilistic model for the turbulence. Several probability density functions (PDFs) have been proposed for the intensity variations at the receiver of an optical link [6]–[11]. Al-Habash *et al.* [12] proposed a statistical model that factorizes the irradiance as the product of two independent random processes each with a Gamma probability density function (PDF). The PDF of the intensity fluctuation is therefore

$$f(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\alpha+\beta)/2-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right), \qquad I > 0, \tag{2.2}$$

where I is the signal intensity, α and β are parameters of the PDF, $\Gamma(\cdot)$ is the Gamma function, and $K_{\alpha-\beta}(\cdot)$ is the modified Bessel function of the second kind of order $\alpha - \beta$.

The parameters α and β of the PDF that predicts the scintillation experienced by plane waves in the case of $l_0 = 0$, are given by the expressions [4],[5]

$$\alpha = \left(\exp\left[\frac{0.49\sigma_R^2}{(1 + 1.11\sigma_R^{12/5})^{7/6}}\right] - 1\right)^{-1} \quad \text{and}$$

$$\beta = \left(\exp\left[\frac{0.51\sigma_R^2}{(1 + 0.69\sigma_R^{12/5})^{5/6}}\right] - 1\right)^{-1}, \tag{2.3}$$

where σ_R^2 is the Rytov variance as given in Eq. (2.1). This is a very interesting expression, because the PDF of the intensity fluctuations at the receiver can be predicted from the physical turbulence conditions. The predicted distribution matches very well the distributions obtained from numerical propagation simulations and experiments [1],[6].

2.2 Codes on graphs

The codes on graphs of interest in optical communications include turbo codes, turbo-product codes, and LDPC codes. Turbo codes [25],[26] can be considered as the generalization of the concatenated codes, where during iterative decoding the decoders exchange the soft messages for a certain number of times. Turbo codes can approach channel capacity closely in the region of interest for wireless communications. However, they exhibit strong error floors in the region of interest for optical communications; therefore, alternative iterative soft decoding approaches are to be sought. As recently shown in [16]–[24], turbo-product codes and LDPC codes can provide excellent coding gains and, when properly designed, do not exhibit an error floor in the region of interest for optical communications.

A turbo-product code (TPC) is an $(n_1 n_2, k_1 k_2, d_1 d_2)$ code in which codewords form an $n_1 \times n_2$ array such that each row is a codeword from an (n_1, k_1, d_1) code C_1, and each column is a codeword from an (n_2, k_2, d_2) code C_2. With n_i, k_i and d_i $(i = 1, 2)$ we denoted the codeword length, dimension, and minimum distance, respectively, of the ith component code. The soft bit reliabilities are iterated between decoders for C_1 and C_2. In optical communications, TPCs based on BCH component codes have been intensively studied, e.g. [25],[26].