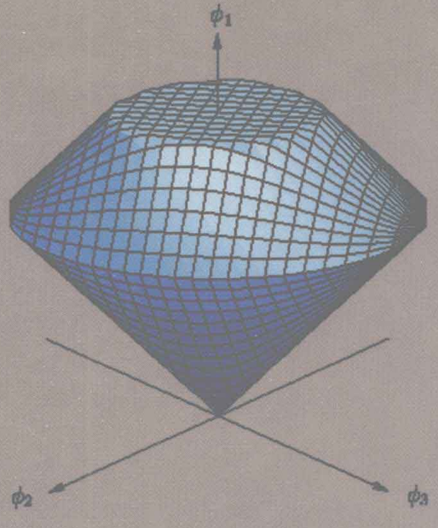
Wireless Optical Communication Systems

Steve Hranilovic



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Preface

The use of optical free-space emissions to provide indoor wireless communications has been studied extensively since the pioneering work of Gfeller and Bapst in 1979 [1]. These studies have been invariably interdisciplinary involving such far flung areas such as optics design, indoor propagation studies, electronics design, communications systems design among others. The focus of this text is on the design of communications systems for indoor wireless optical channels. Signalling techniques developed for wired fibre optic networks are seldom efficient since they do not consider the bandwidth restricted nature of the wireless optical channel. Additionally, the elegant design methodologies developed for electrical channels are not directly applicable due to the amplitude constraints of the optical intensity channel. This text is devoted to presenting optical intensity signalling techniques which are *spectrally efficient*, i.e., techniques which exploit careful pulse design or spatial degrees of freedom to improve data rates on wireless optical channels.

The material presented here is complementary to both the comprehensive work of Barry [2] and to the later book by Otte *et al.* [3] which focused primarily on the design of the optical and electronic sub-systems for indoor wireless optical links. The signalling studies performed in these works focused primarily on the analysis of popular signalling techniques for optical intensity channels and on the use of conventional electrical modulation techniques with some minor modifications (e.g., the addition of a bias). In this book, the design of spectrally efficient signalling for wireless optical intensity channels is approached in a fundamental manner. The goal is to extend the wealth of modem design practices from electrical channels to optical intensity domain. Here we discuss important topics such as the vector representation of optical intensity signals, the design and capacity of signalling sets as well as the use of multiple transmitter and receiver elements to improve spectral efficiency.

Although this book is based on my doctoral [4] and Masters [5] theses, it differs substantially from both in several ways. Chapters 2 and 3 are completely re-written and expanded to include a more tutorial exposition of the basic issues involved in signalling on wireless optical channels. Chapters 4-6, which develop the connection between electrical signalling design and optical intensity channels, are significantly re-written in more familiar language to allow them to be more accessible. Chapters 7 and 8 are improved through the addition of a fundamental analysis of MIMO optical channels and the increase in capacity which arise due to spatial multiplexing in the presence of spatial bandwidth constraints. Significant background material has been added on the physical aspects of wireless optical channels including optoelectronic components and propagation characteristics to serve as an introduction to communications specialists. Additionally, fundamental communication concepts are briefly reviewed in order to make the signalling design sections accessible to experimentalists and applied practitioners.

Finally, there have been a great number of individuals who have influenced the writing of this book and deserve my thanks. I am very grateful to my doctoral thesis advisor Professor Frank R. Kschischang who's passion for research and discovery have inspired me. Additionally, I would like to thank Professors David A. Johns and Khoman Phang for introducing me to the area and for fostering my early explorations in wireless optical communications. I am also indebted to a number of friends and colleagues who have contributed through many useful conversations, among them are : Warren Gross, Yongyi Mao, Andrew Eckford, Sujit Sen, Tooraj Esmailian, Terence Chan, Masoud Ardakani and Aaron Meyers.

Foremost, I would like to thank my wife Annmarie for her patience, understanding and for her support.

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About the Author

Steve Hranilovic is an Assistant Professor in the Department of Electrical and Computer Engineering, McMaster University, Hamilton, Ontario, Canada. He received the B.A.Sc. degree with honours in electrical engineering from the University of Waterloo, Canada in 1997 and M.A.Sc. and Ph.D. degrees in electrical engineering from the University of Toronto, Canada in 1999 and 2003 respectively. From 1992 to 1997, while studying for the B.A.Sc. degree, he worked in the areas of semiconductor device characterization and microelectronics for Nortel Networks and the VLSI Research Group, University of Waterloo. As a graduate student, Dr. Hranilovic received the Natural Sciences and Engineering Research Council of Canada postgraduate scholarships, Ontario Graduate Scholarship in Science and Technology, the Walter C. Sumner Foundation fellowship and the Shahid U. Qureshi Scholarship for Research in Communications. Dr. Hranilovic's research interests are in the areas of free-space and wired optical communications, digital communications algorithms, and electronic and photonic implementation of coding and communication algorithms.

From August 2000 until August 2003, Dr. Hranilovic served as co-Chair of the IEEE Communications Society, Toronto Chapter.

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PART I

INTRODUCTION

Chapter 1

INTRODUCTION

In recent years, there has been a migration of computing power from the desktop to portable, mobile formats. Devices such as digital still and video cameras, portable digital assistants and laptop computers offer users the ability to process and capture vast quantities of data. Although convenient, the interchange of data between such devices remains a challenge due to their small size, portability and low cost. High performance links are necessary to allow data exchange from these portable devices to established computing infrastructure such as backbone networks, data storage devices and user interface peripherals. Also, the ability to form *ad hoc* networks between portable devices remains an attractive application. The communication links required can be categorized as short-range data interchange links and longer-range wireless networking applications.

One possible solution to the data interchange link is the use of a direct electrical connection between portable devices and a host. This electrical connection is made via a cable and connectors on both ends or by some other direct connection method. The connectors can be expensive due to the small size of the portable device. In addition, these connectors are prone to wear and break with repeated use. The physical pin-out of the link is fixed and incompatibility among various vendors solutions may exist. Also, the need to carry the physical medium for communication makes this solution inconvenient for the user.

Wireless radio frequency (RF) solutions alleviate most of the disadvantages of a fixed electrical connection. RF wireless solutions allow for indoor and short distance links to be established without any physical connection. However, these solutions remain relatively expensive and have low to medium data rates. Some popular "low cost" RF links over distances of approximately 10 m provide data rates of up to 1 Mbps in the 2.4 GHz band for a cost near US$5 per module. Indoor IEEE 802.11 [6] links have also gained significant popularity

Table 1.1. Comparison of wireless optical and radio channels.

Property	Wireless Optical	Radio
Cost	$	$$
RF circuit design	No	Yes
Bandwidth Regulated	No	Yes
Data Rates	100's Mbps	10's Mbps
Security	High	Low
Passes through walls ?	No	Yes

and provide data rates of approximately 50 Mbps. Radio frequency wireless links require that spectrum licensing fees are paid to federal regulatory bodies and that emissions are contained within strict spectral masks. These frequency allocations are determined by local authorities and may vary from country to country, making a standard interface difficult. In addition, the broadcast nature of the RF channel allows for mobile connectivity but creates problems with interference between devices communicating to a host in close proximity. Containment of electromagnetic energy at RF frequencies is difficult and if improperly done can impede system performance.

This book considers the use of wireless optical links as another solution to the short-range interchange and longer-range networking links. Table 1.1 presents a comparison of some features of RF and wireless optical links. Present day wireless optical links can transmit at 4 Mbps over short distances using optoelectronic devices which cost approximately US$1 [7]. However, much high rates approaching 1 Gpbs have been investigated in some experimental links. Wireless optical links transmit information by employing an optoelectronic light modulator, typically a light-emitting diode (LED). The task of up- and down-conversion from baseband frequencies to transmission frequencies is accomplished without the use of high-frequency RF circuit design techniques, but is accomplished with inexpensive LEDs and photodiodes. Since the electromagnetic spectrum is not licensed in the optical band, spectrum licensing fees are avoided, further reducing system cost. Optical radiation in the infrared or visible range is easily contained by opaque boundaries. As a result, interference between adjacent devices can be minimized easily and economically. Although this contributes to the security of wireless optical links and reduces interference it also impacts rather stringently on the mobility of such devices. For example, it is not possible for a wireless optical equipped personal digital assistant to communicate if it is stored in a brief case. Wireless optical links are also suited to portable devices since small surface mount light emitting and light detecting components are available in high volumes at relatively low cost.

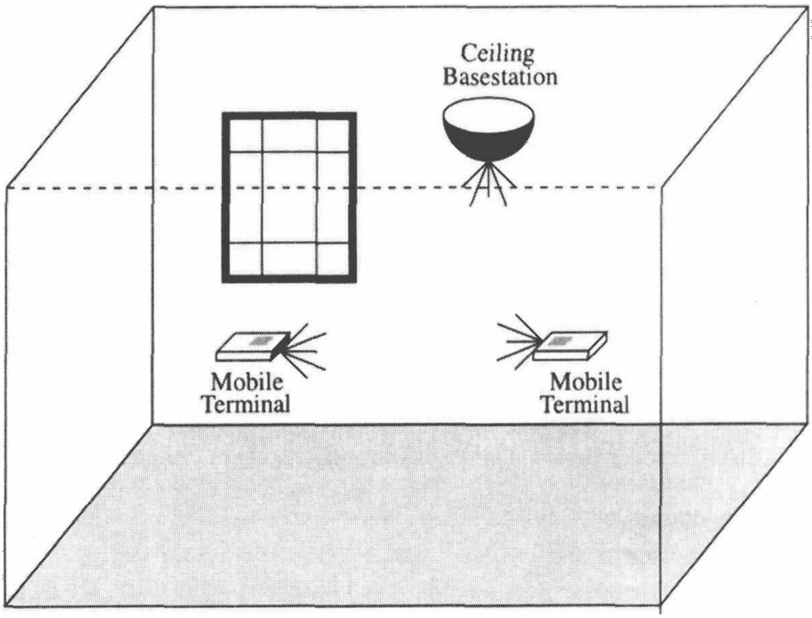

Figure 1.1. An indoor wireless optical communication system.

Figure 1.1 presents a diagram of a typical indoor wireless optical communications scenario. Mobile terminals are allowed to roam inside of a room and require that links be established with a ceiling basestation as well as with other mobile terminals. In some links the radiant optical power is directed toward the receiver, while in others the transmitted signal is allowed to bounce diffusely off surfaces in the room. Ambient light sources are the main source of noise in the channel and must be considered in system design. However, the available bandwidth in some directed wireless optical links can be large and allows for the transmission of large amounts of information, especially in short range applications.

Indoor wireless optical communication systems are envisioned here as a complimentary rather than a replacement technology to RF links. Whereas, RF links allow for greater mobility wireless optical links excel at short-range, high-speed communications such as in device interconnection or board-to-board interconnect.

1.1 A Brief History of Wireless Optical Communications

The use of optical emissions to transmit information has been used since antiquity. Homer, in the *Iliad*, discusses the use of optical signals to transmit a message regarding the Grecian siege of Troy in approximately 1200 BC. Fire beacons were lit between mountain tops in order to transmit the message

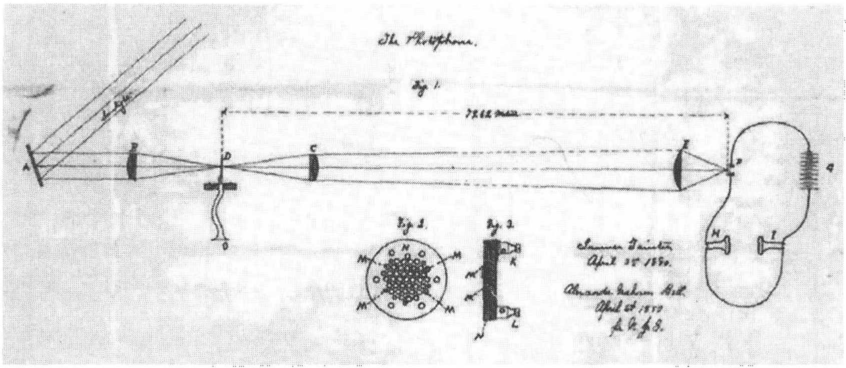

Figure 1.2. Drawing of the photophone by Alexander Graham Bell and Charles Sumner Tainter, April 1880 [The Alexander Graham Bell Family Papers, Library of Congress].

over great distances. Although the communication system is able to only ever transmit a single bit of information, this was by far the fastest means to transmit information of important events over long distances.

In early 1790's, Claude Chappe invented the optical telegraph which was able to send messages over distances by changing the orientation of signalling "arms" on a large tower. A code book of orientations of the signalling arms was developed to encode letters of the alphabet, numerals, common words and control signals. Messages could be sent over distances of hundreds of kilometers in a matter of minutes [8].

One of the earliest wireless optical communication devices using electronic detectors was the *photophone* invented by A. G. Bell and C. S. Tainter and patented on December 14, 1880 (U.S. patent 235,496). Figure 1.2 presents a drawing made by the inventors outlining their system. The system is designed to transmit a operator's voice over a distance by modulating reflected light from the sun on a foil diaphragm. The receiver consisted of a selenium crystal which converted the optical signal into an electrical current. With this setup, they were able to transmit an audible signal a distance of 213 m [9].

The modern era of indoor wireless optical communications was initiated in 1979 by F.R. Gfeller and U. Bapst by suggesting the use of diffuse emissions in the infrared band for indoor communications [1]. Since that time, much work has been done in characterizing indoor channels, designing receiver and transmitter optics and electronics, developing novel channel topologies as well as in the area of communications system design. Throughout this book, previous work on a wide range of topics in wireless optical system will be surveyed.

1.2 Overview

The study of wireless optical systems is multidisciplinary involving a wide range of areas including: optical design, optoelectronics, electronics design, channel modelling, communications and information theory, modulation and equalization, wireless optical network architectures among many others.

This book focuses on the issues of signalling design and information theory for wireless optical intensity channels. This book differs from Barry's comprehensive work *Wireless Infrared Communications* [2] and the text by Otte *et al.* *Low-Power Wireless Infrared Communications* by focusing exclusively on the design of modulation and coding for single element and multi-element wireless optical links. This work is complimentary and focuses on the design of signalling and communication algorithms for wireless optical intensity channels.

The design of a communication algorithms for any channel first requires knowledge of the channel characteristics. Chapter 2 overviews the basic operation of optoelectronic devices and the amplitude constraints that they introduce. Eye and skin safety, channel propagation characteristics, noise and a variety of channel topologies are described.

Most signalling techniques for wireless optical channels are adapted from wired optical channels. Conventional signalling design for the electrical channel cannot be applied to the wireless optical intensity channel due to the channel constraints. A majority of signalling schemes for optical intensity channels deal with binary-level on-off keying or PPM. Although power efficient, their spectral efficiency is poor. Chapter 3 overviews basic concepts in communications system design such as vector channel model, signal space, bandwidth as well a presenting an analysis of some popular binary and multi-level modulation schemes.

Part II of this book describes techniques for the design and analysis of spectrally efficient signalling techniques for wireless optical channels. This work generalizes previous work in optical intensity channels in a number of important ways. In Chapter 4, a signal space model is defined which represents the amplitude constraints and the cost geometrically. In this manner, all time-disjoint signalling schemes for the optical intensity channel can be treated in a common framework, not only rectangular pulse sets.

Having represented the set of transmittable signals in signal space, Chapter 5 defines lattice codes for optical intensity channels. The gain of these codes over a baseline is shown to factor into coding and shaping gains. Unlike previous work, the signalling schemes are not confined to use rectangular pulses. Additionally, a more accurate bandwidth measure is adopted which allows for the effect of shaping on the spectral characteristics to be represented as an effective dimension. The resulting example lattice codes which are defined show that on an idealized point-to-point link significant rate gains can be had by using spectrally efficient pulse shapes.

Chapter 6 presents bounds on the capacity of optical intensity signalling sets subject to an average optical power constraint and a bandwidth constraint. Although the capacity of Poisson photon counting channels has been extensively investigated, the wireless optical channel is Gaussian noise limited and pulse sets are not restricted to be rectangular. The specific bounds on the channel capacity of wireless optical channels exist for the case of PPM signalling and multiple-subcarrier modulation. The bounds presented in this work generalize these previous results and allow for the direct comparison of convention rectangular modulation with more spectrally efficient schemes. The bounds are shown to converge at high optical signal-to-noise ratios. Applied to several examples, the bounds illustrate that spectrally efficient signalling is necessary to maximize transmit rate at high SNR.

The spectral efficiency and reliability of wireless optical channels can also be improved by using multiple transmitter and receiver elements. Part III considers the modelling and signalling problem of multi-element links. Chapter 7 discusses the use of multiple transmit and receive elements to improve the efficiency of wireless optical links and presents a discussion on the challenges which are faced in signalling design.The pixelated wireless optical channel is defined as a multi-element link which improves the spectral efficiency of links unlike previous multi-element links, such as quasi-diffuse links and angle diversity schemes,. Although chip-to-chip, inter-board and holographic storage systems exploit spatial diversity for gains in data rate, the pixelated wireless optical channel does not rely on tight spatial alignment or use a pixel-matched assumption. Chapter 8 presents an experimental multi-element link in order to develop a channel model based on measurements. Using this channel model pixel-matched and pixelated optical spatial modulation techniques are compared.

Finally, Chapter 9 presents concluding remarks and directions for further study.