BOSTON UNIVERSITY

COLLEGE OF ENGINEERING

Dissertation

OPTICAL MIMO COMMUNICATION SYSTEMS UNDER ILLUMINATION CONSTRAINTS

by

PANKIL M. BUTALA

B.E., University of Mumbai, 2006
M.S., University of California, Los Angeles, 2007

Submitted in partial fulfillment of the

requirements for the degree of

Doctor of Philosophy

2015

Approved by

First Reader

Thomas D.C. Little, Ph.D.
Professor of Electrical and Computer Engineering
Professor of Systems Engineering

Second Reader

Jeffrey Carruthers, Ph.D.
Associate Professor of Electrical and Computer Engineering

Third Reader

Bobak Nazer, Ph.D.
Assistant Professor of Electrical and Computer Engineering
Assistant Professor of Systems Engineering

Fourth Reader

Valencia Joyner Koomson, Ph.D.
Associate Professor of Electrical and Computer Engineering
Tufts University

"Δv - v for velocity, Δ for change. In space, this is the measure of change in velocity required to get from one place to another, thus a measure of the energy required to do it. Everything is moving already but to get something from the moving surface of the Earth into orbit around it requires a minimum Δv of 10km/s. To leave Earth's orbit and fly to Mars requires a minimum Δv of 3.6km/s and to orbit Mars and land on it requires a Δv of about 1 km/s. The hardest part is leaving Earth behind, for that is by far the deepest gravity well involved."

Kim Stanley Robinson
Red Mars (2.2.99) check reference

Acknowledgments

I would like to thank ...

Sincerely,

Pankil

OPTICAL MIMO COMMUNICATION SYSTEMS UNDER ILLUMINATION CONSTRAINTS

PANKIL M. BUTALA

Boston University, College of Engineering, 2015

Major Professor: Thomas D.C. Little, Ph.D.
Professor of Electrical and Computer Engineering
Professor of Systems Engineering

ABSTRACT

In recent years, there has been a large–scale adoption of portable computing devices like smartphones and tablets. These along with internet-of-things need ubiquitous connectivity to the internet to provide value added services, maximize their functionality and create a 'smart'-er world to live in. Cisco's visual networking index predicts wireless data consumption to increase by a cumulative rate of 61% every year. This will put additional stress on the already stressed wireless access network infrastructure creating a phenomenon called 'spectrum crunch'.

On the other hand, solid state devices industry has made remarkable advances in energy efficient light-emitting-diodes (LED). The lighting industry is rapidly adopting LEDs to provide illumination in indoor spaces. Lighting fixtures are positioned to support human activities and thus are well located to act as wireless access points. The visible spectrum (380 nm – 780 nm) is yet unregulated and untapped for wireless access. This provides unique opportunity to upgrade existing lighting infrastructure and create a dense grid of small cells by using this additional 'optical' wireless bandwidth. Under the above model, lighting fixtures will service dual missions of illumination and wireless access points.

This dissertation investigates multiple-input multiple-output (MIMO) optical wireless broadcast system under unique constraints imposed by the optical channel and user illumination requirements. Sample indexed spatial orthogonal frequency division multiplexing and metameric modulation are proposed to achieve higher spectral efficiency by exploiting dimensions of space and color respectively in addition to time and frequency dimensions. A framework is developed to analyze performance of imaging MIMO systems. Performance improvements for optical systems have been achieved by decorrelating spatially separate links by incorporating an imaging receiver. The dissertation also studies the impact of visual perception on performance color shift keying as specified in IEEE 802.15.7 standard. The dissertation then introduces the singular value decomposition based OWC system architecture to incorporate illumination constraints independent of communication constraints in a MIMO system. It then studies design paradigm for a multi–colored wavelength division multiplexed indoor OWC system.

Contents

List of Tables

List of Figures

List of Abbreviations

ACO	....	Asymmetrically Clipped Optical
APD	....	Avalanche Photo Diode
AWGN	....	Additive White Gaussian Noise
CIE	....	Commission Internationale de l'Eclairage
CMOS	....	Complementary Metal Oxide Semiconductor
CP	....	Carrier Prefix
CSI	....	Channel State Information
CSK	....	Color Shift Keying
DCO	....	DC biased Optical
DMT	....	Discrete Multi-Tone
FOV	....	Field Of View
GCS	....	Global Coordinate System
ICI	....	Inter Channel Interference
IID	....	Independent and Identically Distributed
IM/DD	....	Intensity Modulation / Direct Detection
ISI	....	Inter Symbol Interference
LED	....	Light Emitting Diode
LOS	....	Line Of Sight
LSNR	....	Luminous Signal to Noise Ratio
MAC	....	Medium Access Control
MIMO	....	Multiple Input Multiple Output
MM	....	Metameric Modulation
MSM	....	Multiple Subcarrier Modulation
NLOS	....	Non Line Of Sight
NRZ	....	Non-Return to Zero
OFDM	....	Orthogonal Frequency Division Multiplexing
OOK	....	On-Off Keying
PAM	....	Pulse Amplitude Modulation
PCS	....	Primary Color Space
PD	....	Photo Diode
PHY	....	Physical layer
PIN	....	P-I-N Junction
PPM	....	Pulse Position Modulation
PWM	....	Pulse Width Modulation

QAM	Quadrature Amplitude Modulation
RCS	Receiver Coordinate System
RF	Radio Frequency
RZ	Return to Zero
RGB	Red, Green and Blue
SD	Standard Deviation
SISO	Single Input Single Output
SIS	Sample Indexed Spatial
SM	Spatial Modulation
SMP	Spatial Multiplexing
SNR	Signal to Noise Ratio
SPD	Spectral Power Distribution
SSK	Spatial Shift Keying
SVD	Singular Value Decomposition
TIA	Trans-Impedance Amplifier
UCS	Universal Color Space
VCS	Visual Color Space
VLC	Visible Light Communication
VNI	Visual Networking Index
VPPM	Variable Pulse Position Modulation
WDM	Wavelength Division Multiplexing