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Dissertation

OPTICAL MIMO COMMUNICATION SYSTEMS UNDER ILLUMINATION CONSTRAINTS

by

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"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 10 km/s. To leave Earth's orbit and fly to Mars requires a minimum Δv of 3.6 km/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)

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ABSTRACT

Technology for wireless information access has enabled innovation of 'smart' portable consumer devices. These have been widely adopted and have become an integral part of our daily lives. They need ubiquitous connectivity to the internet to provide value added services, maximize their functionality and create a smarter world to live in. Cisco's visual networking index currently predicts wireless data consumption to increase by 61% per year. This will put additional stress on the already stressed wireless access network infrastructure creating a phenomenon called 'spectrum crunch'.

At the same time, the 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 access points for optical wireless communication (OWC).

This dissertation investigates multiple-input multiple-output (MIMO) optical wireless broadcast system under unique constraints imposed by the optical channel and illumination requirements. Sample indexed spatial orthogonal frequency division multiplexing (SIS-OFDM) and metameric modulation (MM) are proposed to achieve higher spectral efficiency by exploiting dimensions of space and color respectively in addition to time and frequency. SIS-OFDM can provide significant additional spectral efficiency of up to (N_{sc}/2 - 1) $\times$ k bits/symbol where N_{sc} is total number of subcarriers and k is number of bits per underlying spatial modulation symbol. MM always generates the true requested illumination color and has the potential to provide better color rendering by incorporating multiple LEDs. A normalization framework is then developed to analyze performance of optical MIMO imaging systems. Performance improvements of up to 45 dB 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. It shows that non-linearity for a practical system can have a performance penalty of up to 15 dB when compared to the simplified linear system abstraction as proposed in the standard. Luminous-signal-to-noise ratio, a novel metric is introduced to compare performance of optical modulation techniques operating at same illumination intensity. The dissertation then introduces 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.

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List of Abbreviations

ACO	....	Asymmetrically Clipped Optical
APD	....	Avalanche Photo Diode
AWGN	....	Additive White Gaussian Noise
CCT	....	Correlated Color Temperature
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
E/O	....	Electrical to Optical
FOV	....	Field Of View
FWHM	....	Full Width at Half Maximum
GCS	....	Global Coordinate System
ICI	....	Inter Channel Interference
IID	....	Independent and Identically Distributed
IM/DD	....	Intensity Modulation / Direct Detection
IR	....	Infra–Red
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
O/E	....	Optical to Electrical
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
UV	....	Ultra–Violet
VCS	....	Visual Color Space
VLC	....	Visible Light Communication
VNI	....	Visual Networking Index
VPPM	....	Variable Pulse Position Modulation
WDM	....	Wavelength Division Multiplexing