Your awesome thesis

Your beautiful name

A thesis submitted for the degree of Doctor of Philosophy.

The University of Edinburgh.

March 15, 2022

Lay Summary

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Abstract

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Declaration of Originality

I hereby declare that the research recorded in this thesis and the thesis itself was composed and originated entirely by myself in the Institute for Digital Communications School of Engineering at The University of Edinburgh.

Name
Edinburgh, UK
March 15, 2022

Acknowledgements

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Acronyms and Abbreviations

3GPP	3^{rd} generation partnership project
ACF	autocorrelation function
ACO	asymmetrically clipped optical
ADC	analog-to-digital converter
AGC	automatic gain controller
AP	access point
APD	avalanche photodiode
ATSSS	access traffic steering, switching and splitting
AWGN	additive white Gaussian noise
BER	bit error ratio
CAD	computer-aided design
CCTV	closed-circuit television
CDF	cumulative distribution function
CIR	channel impulse response
CLI	comman-line interface
CSMA/CA	carrier sense multiple access with collision avoidance
CP	cyclic prefix
DASH	dynamic adaptive streaming over hypertext transfer protocol
DAC	digital-to-analog converter
DC	direct current
DFE	decision feedback equalization
DFT	discrete Fourier transform
DPSS	discrete prolate spheroidal sequences
DSP	digital signal processor
DQO	decomposed quadrature optical
eU	enhanced unipolar
E/O	electrical-to-optical
EESM	exponential effective signal-to-interference-plus-noise ratio metric
ESM	effective signal-to-interference-plus-noise ratio mapping

FCC	federal communications commission
FDE	frequency-domain equalization
FEC	forward error correction
FFT	fast fourier transform
FIR	finite impulse response
FoV	field-of-view
FST	fast session transfer
FTP	file transfer protocol
FWHM	full width at half maximum
GTIM	generalized time index modulation
HetNets	heterogeneous networks
HPF	high-pass filter
HTML	hypertext markup language
HE	high efficiency
HTTP	hypertext transfer protocol
IaaS	infrastructure as a service
IDFT	inverse discrete Fourier transform
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IID	identically independently distributed
IM	index modulation
IM/DD	intensity modulation and direct detection
IP	internet protocol
IQ	in-phase and quadrature
IR	infrared
ISI	inter-symbol interference
ITU-T	International Telecommunication Union - Telecommunication Standardization Sector
KSD	Kolmogorov-Smirnov distance
LC	light communications
LD	laser diode
LDPC	low-density parity-check
LE	linear equalizer
LED	light emitting diode

List of Principal Symbols

$\|\|\cdot\|\|_2$	L2-norm
$\mathbb{1}(\cdot)$	indicator function

Chapter 1
Introduction

1.1 Motivations

Optical wireless communications (OWC) are wireless access technologies that occupy the light spectrum, e.g., the infrared (IR), visible light (VL), or ultraviolet [Chowdhury *et al.*, 2018]. Examples of OWC are IR wireless technology [Gfeller & Bapst, 1979], visible light communications (VLC) [Komine *et al.*, 2001], optical camera communications (OCC) [Leibowitz *et al.*, 2001], and light fidelity (LiFi) [Haas *et al.*, 2016].

1.2 Contributions and Thesis Layout

As previously mentioned, the main goal of this thesis is to calculate an offloading efficiency, which will be postponed until the intermediate studies are presented. In the subsequent chapters, a random orientation model, single-carrier and multi-carrier modulation techniques are presented. The following are logical structures and contributions of this thesis.

Chapter 2: LiFi Channel and System Models

This chapter mostly discusses channel and system models that will be used in the following chapters. The models include the frequency responses and the linear dynamic ranges of the light emitters.

Chapter 3: Random Orientation Model

The next contribution of this thesis is a random orientation model.

Chapter 4: Modulation: Single-Carrier and Multi-Carrier

Having near-realistic assumptions of LiFi channels in terms of both random orientation and random blockage models, the next contribution focuses on modulation techniques for LiFi.

1.3 Publication Lists

In order to sum up the contributions of this thesis, the following are publication lists made throughout my study as well as those that are under preparation.

Open Source Libraries:

[1] **Purwita, A. A.** (2020). `owcsimpy`: a Python simulator for optical wireless communications. `https://github.com/ardimasp/owcsimpy`.

Deliverable:

[1] Garcia, A., Cogalan, T., **Purwita, A. A.**, Mur, D. C., Khalili, H., Sark, V., Gutiérrez, J., Hemadeh, I., Kainulainen, J., Turyagyenda, C., Frank, H., Bian, R., & Ghoraishi, M. (2020), State-of-the-Art Review and Initial Design of the Integrated 5GNR/Wi-Fi/LiFi Network Frameworks on Coexistence, Multi-Connectivity, Resource Management and Positioning. 5G-CLARITY Deliverable D3.1. `https://www.5gclarity.com/wp-content/uploads/2020/09/5G-CLARITY_D3.1.pdf`.

Journal Papers:

[1] **Purwita, A. A.**, Soltani, M. D., Safari, M., & Haas, H. (2019). Terminal Orientation in OFDM- Based LiFi Systems. IEEE Transactions on Wireless Communications, 18(8), 4003- 4016.

Conference Papers:

[1] **Purwita, A. A.**, Chen, C., Basnayaka, D. A., & Haas, H. (2017). Aggregate Signal Interference of Downlink LiFi Networks. In 2017 IEEE Global Communications Conference (GLOBECOM), (p. 1-6). Singapore, Singapore.

Standardization:

[1] **Purwita, A.**, Rossius, A., Haas, H., Serafimovski, N., Afgani, M., Berner, S., ... Uysal, M. (2020). Proposals and related work on Center Frequency for the Common Mode Mandatory PHY. `https://mentor.ieee.org/802.11/dcn/20/11-20-1449-03-00bb-proposals-and-related-work-on-center-frequency-for-the-common-mode-mandatory-phy.pptx`.

Under Preparation:

[1] Purwita, A. A., Cogalan, T., & Haas, H. (2020). Coherence Time of Indoor LiFi Channels. to be submitted.

1.4 Summary

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Chapter 2

LiFi Channel and System Models

2.1 Introduction

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At the time of writing, Institute of Electrical and Electronics Engineers (IEEE) 802.11 Light Communications Amendment - Task Group “bb” (TGbb) has agreed on the operating wavelength spectrum for IEEE 802.11bb. Based on [Serafimovski *et al.*, 2019], the related motion states the following.

> *“Move to adopt the 800nm - 1,000nm wavelength spectrum as the mandatory, common mode wavelength for all TGbb STAs.”*

The first reason is that the responsivity of silicon-based PDs is higher at those ranges compared to that in the VL spectrum as shown in Figure 2.1, which shows four samples of responsivities of different Silicon-based PDs taken from [Edmund Optics®, 2020].

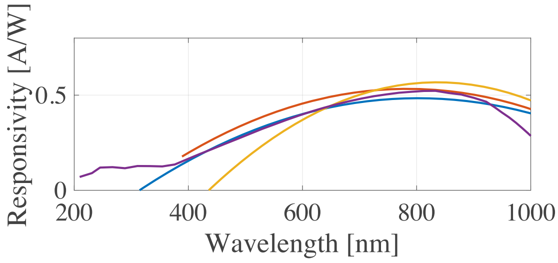


Figure 2.1. Responsivities of four different Silicon-based PDs taken from [Edmund Optics®, 2020]. (Please refer to [Edmund Optics®, 2020] for more detailed information on the corresponding curves. Note that details are removed for clarity purposes.)

2.2 LiFi Channel Model

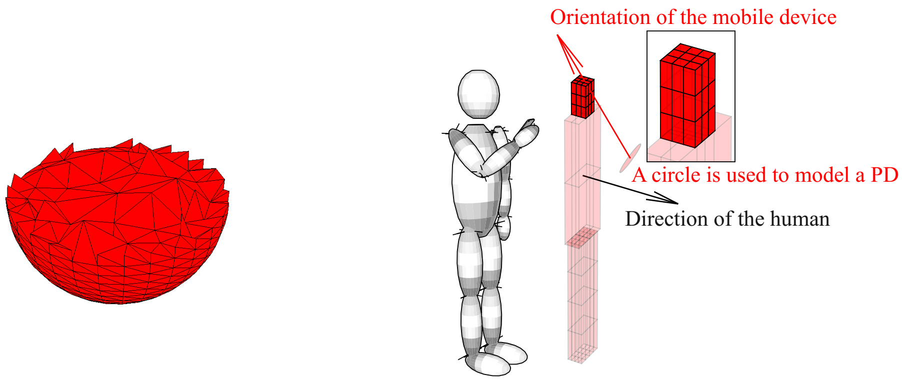
Based on [Kahn, Krause, & Carruthers, 1995; Kahn & Barry, 1997], the received optical power can be expressed as:

$$y(t) = h(t) \circledast x(t), \tag{2.1}$$

where $\circledast$ denotes the convolution operation.

2.2.1 Channel Model

For the sake of the illustrations, different opacities of faces in Figure 2.2(b) show different reflectivities, i.e., the head portions of the models have different reflectivities compared to the body portions of the model.



(a) **(b)**

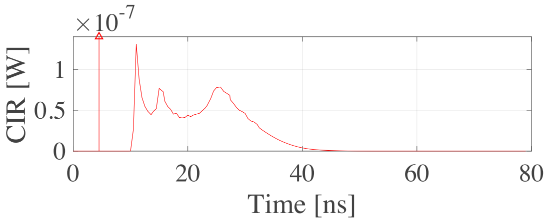
Figure 2.2. (a) An example of a 3D object as a collection of 2D faces, and (b) a human model as a collection of square faces.

Materials:	paint	cotton	skin	plaster	pinewood
Reflectivities (@ 940 nm):	0.04	0.65	0.70	0.85	0.92
Reflectivities (@ 850 nm):	0.04	0.64	0.66	0.83	0.92

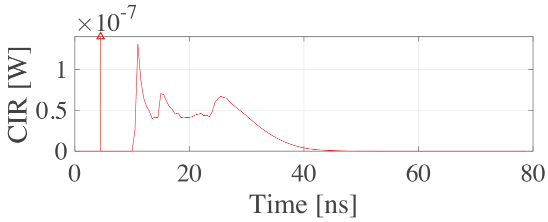
Table 2.1. Reflectivities of materials over visible light (VL) and infrared (IR) spectrum.

2.2.2 A Simple Office Environment

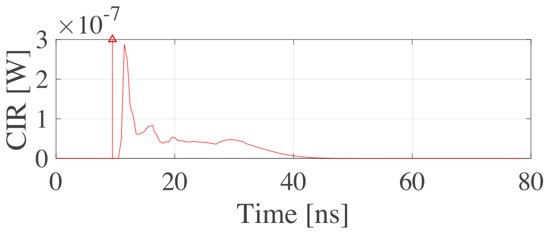
Summaries of the reflectivities of the materials can be found in Table 2.1.



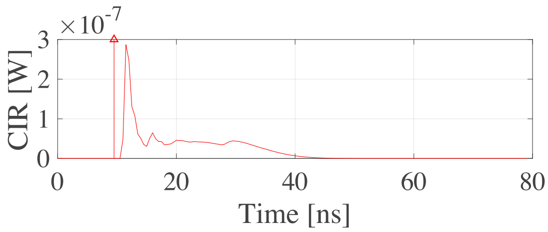
(a) Case 1: 940 nm



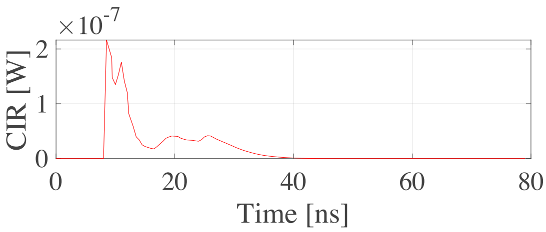
(b) Case 1: 850 nm



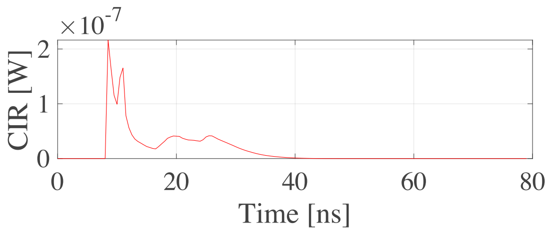
(c) Case 2: 940 nm



(d) Case 2: 850 nm



(e) Case 3: 940 nm



(f) Case 3: 850 nm

Figure 2.3. CIRs.

Appendix A
owcsimpy: A Library for Generating Wireless Optical CIRs

A.1 Introduction

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```
cube = Cube(
    Vector(np.array([1,np.deg2rad(90),np.deg2rad(90)])),
    ctrPoint = np.array([0.5,0.5,0.5]),
    dimensions = [2,1,1],
    RodriguesAngle = np.deg2rad(30),
    reflectivities={’p0’:0.5,’p1’:0.5,’p2’:0.5,
                    ’p3’:0.5,’p4’:0.5,’p5’:0.5}
)
planes = cube.getPartition(2)
fig,ax = draw(planes=planes,alphas=0.2,
    xlim=[-2,2],ylim=[-2,2],zlim=[-2,2],
    azim=-34,elev=9
 )

```

Listing A.1. A Python snippet to generate a cuboid

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