

**LOW COMPLEXITY OF OPTICAL FILTER BANK MULTI-CARRIER (FBMC)
MODULATION FOR VISIBLE LIGHT COMMUNICATION USING LASER
DIODE**

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A thesis submitted in
fulfillment of the requirement for the award of the
Doctor of Philosophy in Electric Engineering



Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

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I dedicate my humble work to Allah Almighty who gave me strength and wisdom to complete this work, to my beloved family, my dear father and mother, to my beloved wife Nabaa and my children (Muhammad, Amna and Montadher), to my brothers Ahmed and Hassan, to my sisters Alaa, Shaima and Belqis for their pure love and prayers that helped me along the way, to my supervisors for patience and directing them to me, to my friends and colleagues for their love and devotion that drove me to finish my work.



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ACKNOWLEDGMENT

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ABSTRACT

DC-bias Optical Filter Bank Multi-carrier (DCO-FBMC) was used as a modulation technology compatible with Intensity Modulation/Direct Detection (IM/DD) that will provide a high data rate for visible light communication (VLC). The DCO-FBMC modulation is one of the most effective modulation techniques, but power consumption is the obstacle facing the current development. The FBMC modulation deals with Hermitian Symmetry to generate a real signal, which leads to higher power consumption. As well modelling the distribution of luminaires in VLC is challenging in terms of dark spots (especially in the middle and at the edges of the room), besides higher power consumption. Therefore, problem of using Hermitian symmetry was addressed using the complex signal out of the traditional FBMC modulation in the time domain by separating the signal's real part from the complex signal. As a result, the real and imaginary parts are aligned, thus gaining a real FBMC signal. This proposed technique reduces complexity by 57%, leading to a reduction in power consumption. In addition, a unipolar technique was also proposed to treat the power consumption resulting from the use of DC bias, called Flip-FBMC. This method separates the positive part of the real FBMC signal from the negative part and then inverting and merging it with the positive part. Thus, a unipolar signal is obtained without using DC bias. To address the problem of illumination distribution, a laser diode (LD) was used in two proposed scenarios, where scenario 2 was designed using five luminaires, while scenario 3 was designed with 13 luminaires using the optical FBMC modulation technique. The optimal semi-angle and FOV for each scenario improved the illumination distribution, power and SNR distribution. As a result, the power consumption was reduced by 13.1944% for scenario 2 and 18.75% for scenario 3, respectively, compared to the previous scenarios.

ABSTRAK

Bank penapis berbilang pembawa pincang arus terus (DCO-FBMC) telah digunakan sebagai teknologi modulasi yang sesuai dengan modulasi keamatan / pengesanan langsung (IM / DD) mempunyai kadar data yang tinggi untuk komunikasi cahaya nampak (VLC). Modulasi DCO-FBMC adalah salah satu teknik modulasi yang paling berkesan, tetapi penggunaan kuasa adalah halangan dalam pembangunan semasa. Modulasi FBMC berasaskan simetri Hermitian untuk menjana isyarat nyata, yang membawa kepada penggunaan kuasa yang lebih tinggi. Selain itu, memodelkan sebaran cahaya dalam VLC juga mencabar dari segi bintik gelap (terutamanya di bahagian tengah dan di tepi bilik), selain penggunaan kuasa yang lebih tinggi. Oleh itu, masalah menggunakan simetri Hermitian tedah ditangani menggunakan isyarat kompleks daripada modulasi FBMC tradisional dalam domain masa dengan memisahkan bahagian isyarat nyata dari isyarat kompleks. Akibatnya, bahagian isyarat nyata dan khayalan diselaraskan, dengan itu isyarat FBMC nyata diperolehi. Teknik yang dicadangkan ini mengurangkan kekompleksan sebanyak 57%, membawa kepada pengurangan penggunaan kuasa. Di samping itu, teknik ekakutub juga dicadangkan untuk mengurangkan penggunaan kuasa yang disebabkan oleh penggunaan pincang DC, yang dipanggil *Flip-FBMC*. Kaedah ini memisahkan bahagian isyarat positif nyata FBMC daripada bahagian negatif dan kemudian menyongsangkan dan menggabungkannya dengan bahagian positif. Oleh itu, isyarat ekakutub diperoleh tanpa menggunakan pincang DC. Untuk mengatasi masalah sebaran cahaya, diod laser (LD) digunakan dalam dua senario yang dicadangkan, di mana senario 2 direka menggunakan lima lampu dan senario 3 menggunakan 13 lampu menggunakan teknik modulasi FBMC optik. Sudut separa dan FOV yang optimum untuk setiap senario meningkatkan sebaran pencahayaan, kuasa dan SNR. Hasilnya, penggunaan kuasa telah dikurangkan sebanyak 13.1944% untuk senario 2 dan 18.75% untuk senario 3 berbanding senario sebelumnya.

CONTENTS

TITLE	i
DECLARATION	ii
DEDICATION	iii
ACKNOWLEDGMENT	iv
ABSTRACT	v
ABSTRAK	vi
CONTENTS	vii
LIST OF TABLES	xi
LIST OF FIGURES	xiii
LIST OF ABBREVIATIONS	xix
LIST OF SYMBOLS	xxii
LIST OF APPENDICES	xxiii
CHAPTER 1 INTRODUCTION	1
1.1 Introduction	1
1.2 Problem Statement	5
1.3 Objectives	6
1.4 Scopes of Research	6
1.5 Significance of the Research	7
1.6 Thesis Structure Outline	10
CHAPTER 2 LITERATURE REVIEW	12
2.1 Introduction	12
2.2 Optical Transmitters	15
2.2.1 Light Source	15
2.2.2 VLC Optical Modulation	19
2.3 General Characteristic Comparison between FBMC and OFDM	30
2.4 Effect of Size IFFT/FFT	31

2.4.1	Filter Bank Multicarrier Modulation	32
2.4.2	Magnitude Responses of Prototype Filters of FBMC and OFDM	40
2.5	Light Signal Model in an Optical Channel	44
2.5.1	Basic Properties of SSL	44
2.5.2	Illuminance Lighting	45
2.5.3	Channel Characteristics VLC	47
2.6	Optical Receiver	53
2.7	Patterns of Distribution of Illumination Units	54
2.8	Previous Research Work	56
2.8.1	Research Gap	64
2.9	Summary	65
CHAPTER 3	RESEARCH METHODOLOGY	66
3.1	Introduction	66
3.2	Research Framework for FBMC Modulation	66
3.3	Real FBMC Signal	68
3.3.1	Hermitian Symmetry	68
3.3.2	New Technique Imaginary to Real Converter (Im2ReC)	71
3.4	FBMC Complexity	76
3.5	PAPR of the FBMC Modulation	77
3.6	Unipolar FBMC Techniques Signal	79
3.6.1	DC-Bias Optical FBMC Communication	79
3.6.2	Flip-FBMC Technique Unipolar	82
3.6.3	Unipolar Efficient	85
3.7	Indoor VLC Channel Model	88
3.7.1	Four Illumination Units Model	90
3.7.2	Five Illumination Units Model	91
3.7.3	New 13 Illumination Unit Configuration Model	93
3.8	Optical Receiver for Visible Light Communication	95
3.9	Evaluation Characteristic	96
3.10	Uniformity Factor	98
3.10.1	Illumination Uniformity	98

3.10.2 Optical Power Uniformity	98
3.10.3 SNR Uniformity	99
3.11 Optimise Semi-angle and FOV	99
3.11.1 Optimise Semi-angle VLC Model	100
3.11.2 Optimise FOV VLC Model	100
3.12 Power Consumption for Proposed Method	100
3.13 Root Mean Square VLC Channel	101
3.14 Summary	102
CHAPTER 4 RESULTS AND DISCUSSION	104
4.1 Introduction	104
4.2 BER Performance FBMC vs OFDM	104
4.3 VLC Im2ReC-FBMC Modulation	107
4.3.1 Low Complexity Real Signal FBMC Modulation VLC System	107
4.3.2 PAPR and BER Performance	110
4.4 Efficient of Unipolar VLC Schemes	113
4.5 Optical VLC Channel Characteristic Performance	115
4.5.1 Illumination VLC Performance	115
4.5.2 Effective Illumination Distribution in the Typical Room	123
4.5.3 Received Optical Power	126
4.5.4 Power Consumption	145
4.5.5 SNR Analysis of Indoor Scenarios	146
4.5.6 The Relationship between the Elements of the Channel Model	155
4.5.7 RMS Spread and Rb Analyses	163
4.5.8 BER for Proposed Scenarios	165
4.6 Summary	169
CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS	171
5.1 Introduction	171
5.2 Conclusions	171
5.3 Research Contributions	172
5.4 Recommendation for Future Directions	173

REFERENCES	175
APPENDICES	191



LIST OF TABLES

2.1	Presents the difference between VLC and RF	13
2.2	Summary of previous research work on the white light generator	18
2.3	Most different points between LD and LED.	19
2.4	Simulation parameters of OFDM and FBMC	37
2.5	K-coefficient overlapping	37
2.6	VLC environmental of indoor channel	47
2.7	Comparison among communal modulation kinds	57
2.8	FBMC proposed modelled and comparison with previous modelled system	60
2.9	Comparison of the literature and reference to the previously modelled method	61
3.1	Parameter of optical transmitters and receivers for indoor application	92
3.2	Parameter of optical transmitters and receiver for indoor VLC system	93
3.3	Characteristics of new configuration indoor VLC system model	95
4.1	Illumination distribution for Scenario 2	119
4.2	Illumination distribution for Scenario 3	121
4.3	Illumination level at the center of the room for different semi-angles values	123
4.4	The overall power consumption of the various configuration models	145
4.5	Verifies the received power	146
4.6	Validation received SNR scenarios	154
4.7	FBMC system complexity performance	170

4.8	Summary of the results of the two scenarios	170
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LIST OF FIGURES

1.1	Smart device is used in the indoor environment	1
1.2	Global data traffic from 2017 to 2022 (in Exabytes per year)	2
1.3	VLC system schemes	4
1.4	The proposed methods model in typical room K-chart	9
2.1	Visible Light Communication survey	14
2.2	RGB method to produce white laser diode	17
2.3	Second method to generate white laser diode	17
2.4	PPM VLC modulation structure	23
2.5	PAM modulation block diagram	24
2.6	CAP modulation block diagram	25
2.7	Block diagram DCO-OFDM modulation	25
2.8	Block diagram optical Flip-OFDM	27
2.9	Block diagram of OQAM/OFDM	30
2.10	EVM function for (a) IFFT bit and (b) FFT bit	32
2.11	QAM in (OFDM) and OQAM in (FBMC) carriers mapping	33
2.12	FBMC subchannel K=2 and M=8	35
2.13	FBMC subchannel at K=4 and M=16	35
2.14	OFDM subchannel at K=2 and M=8	36
2.15	OFDM subchannel at K=4 and M=16	36
2.16	PSD of OFDM	37
2.17	PSD of FBMC at overlapping factors (a) K =2 and (b) K=4	38
2.18	PSD of OFDM at M=16	38
2.19	PSD of FBMC at K=2	39
2.20	PSD of FBMC for Overlapping Factors at (a) K=3, (b) K=4, (c) K=5, (d) K=6, and (e) K=8	40
2.21	Magnitude response FBMC and OFDM of prototype filters for K=2 and M=16	41

2.22	Magnitude response FBMC and OFDM at M=16 and prototype filters for(a) K=3, (b) K=4, (c) K=5, (d) K=6, (e) K=8	42
2.23	Filter bank response for different overlapping factors	43
2.24	Indicates the PSD of FBMC, UFMC, F-OFDM, and OFDM shows how FBMC outperforms them in terms of less spectral leakage and other advantages	43
2.25	Lambertian emitter profile	46
2.26	Propagation of indoor optical link	50
2.27	LEDs unit design (a) hollow design (b) square design	53
2.28	Display the pattern distribution for rectangular and circular distribution	55
2.29	The patterns of distribution of lighting units in the typical room	56
3.1	Framework of optical FBMC modulation	67
3.2	Real and imaginary output signal by using Hermitian Symmetry	69
3.3	Block diagram of FBMC Hermitian Symmetry real signal	70
3.4	New Im2ReC optical FBMC transmitter modulation for real signal in the time domain	71
3.5	Real and Imaginary of Im2ReC signal after separated	72
3.6	The output signal Optical FBMC modulation real signal for Im2ReC technique	73
3.7	Block diagram Im2ReC of optical FBMC receiver	74
3.8	Block diagram of Im2ReC methods	75
3.9	DCO-FBMC block diagram	81
3.10	DC-bias levels (a) 5 dB DC-bias level (b) 7 dB DC-bias level (c) 11dB DC-bias level	82
3.11	New Flip-FBMC modulation technique in VLC	84
3.12	Output Flip-FBMC signal in the time domain	85
3.13	Flowchart of VLC channel model	89
3.14	Typical room with four illumination units	90
3.15	Typical room with Five illumination units	92
3.16	New optical configuration model	94

4.1	BER of DCO-OFDM VS DCO-FBMC	105
4.2	Comparing the multiplication between the conventional method (Conv Tech) and the Im2ReC on the side of the FBMC transmitter, as it is clear that the conventional method of multiplication in it is up to double	108
4.3	Comparing the multiplication between the conventional method (Conv Tech) and the Im2ReC on the side of the FBMC receiver	109
4.4	Comparing the additions between the conventional method (Conv Tech) and the Im2ReC on the side of the FBMC transmitter and receiver	109
4.5	The computational complexity of each bit savings for Im2ReC	110
4.6	The CCDF curves of the conventional method (Conv Tech) and the Im2ReC without Hermitian Symmetry	111
4.7	shows the PDF function of both Im2ReC and conventional methods (Conv Tech) for real FBMC signals	111
4.8	BER as a function of SNR of Conventional method (Conv), and Im2ReC	112
4.9	BER performance of Flip-FBMC vs DCO-FBMC	113
4.10	Electrical to optical efficiency δ_{dc} for different DC-bias levels	114
4.11	The DCO-FBMC power consumption when increasing the DC-Bias level	114
4.12	Illustrated the difference in average power level between DCO-FBMC and Flip-FBMC	115
4.13	The illumination distribution of the typical room, where max = 986.6174lx and the min = 163.1195lx	116
4.14	The illumination level vs half semi-angle	117
4.15	Illumination distribution for scenario 2 at half semi-angle 12.5°	118
4.16	Illumination distribution for scenario 2 at half semi-angle 70°	119
4.17	The effect of the half semi-angle vs average luminance levels in scenario 2	119
4.18	Distribution of indoor illumination in the center of the room	120

4.19	Illumination distribution for scenario 3 at half semi-angle 12.5°	121
4.20	Illumination distribution for scenario 3 at half semi-angle 70°	121
4.21	Average illumination distribution indoor the room	122
4.22	Central illumination distribution indoor the room	122
4.23	The levels of illumination distribution in the centre of the typical room	124
4.24	Average luminance level distribution	124
4.25	Illumination Uniformity distribution	126
4.26	The effect of changing the LD semi-angle on N_{UP}	127
4.27	Effect changing the LD semi-angle on average power	128
4.28	Optimization of semi-angle for five unit's uniformity	128
4.29	Optimum angle at semi-angle 43°	129
4.30	The non-uniformity for scenario 3	129
4.31	Effect of semi-angle for average optical power on scenario 3	130
4.32	Optimization for variation semi-angle for scenario 3	130
4.33	The optimum semi-angle at 50° for scenario 3	131
4.34	Variation FOV received optical power at the centre of the room for scenario 2	132
4.35	Behaviour FOV received optical power at the centre of the room for scenario 3	133
4.36	The optimum FOV for both Scenario 2 and Scenario 3	134
4.37	The behaviour of optimum FOV for both (a) Scenario 2 and (b) Scenario 3	134
4.38	Received optical power at the semi-angle 12.5°	135
4.39	Optical power distribution at the semi-angle 12.5°	136
4.40	Received optical power distribution at semi-angle 70°	136
4.41	Optical power distribution for 13LD units at semi-angle 12.5°	137
4.42	Contour analysis for received optical power distribution for 13LD units at semi-angle 12.5°	138
4.43	Optical power distribution at optimal FOV for Scenario 3 at semi-angle 70°	138
4.44	Average received optical power of scenario 2 and scenario 3	139

4.45	Minimum power behaviour distribution for scenario 2 and scenario 3	140
4.46	Minimum received optical power behaviour for scenario 2 and scenario 3	141
4.47	Maximum received optical power distribution at optimum FOV for both scenarios at optimum semi-angle	142
4.48	The behaviour of power distribution at the centre of the room versus a semi-angle	142
4.49	Verification received optical power distribution at the centre of the room	143
4.50	Verification average received optical power distribution at the room	144
4.51	Side view received optical power distribution (a) minimum side view optical power distribution (b) maximum side view optical power distribution	144
4.52	SNR of scenario2 at (a) semi-angle 12.5° (b) semi-angle 80°	147
4.53	SNR scenario 2 at optimum values FOV and semi-angle	147
4.54	SNR of scenario 3 at (a) semi-angle 12.5° (b) semi-angle 80°	148
4.55	SNR scenario 3 at optimum values FOV and semi-angle	149
4.56	Show minimum distribution SNR for various semi-angle	149
4.57	Average SNR distribution of various semi-angle	150
4.58	SNR centre distribution of the room	150
4.59	Average SNR distribution at the room for various semi-angle	151
4.60	Centre SNR distribution at the room for various semi-angle	152
4.61	CV_{SNR} uniformity distribution of typical room	152
4.62	Investigation CV_{SNR} scenarios vs various semi-angle	153
4.63	SNR distribution at typical room (a) minimum SNR distribution (b) Max SNR distribution	154
4.64	The relationship (a) Average SNR vs Average optical power, (b) Average illumination vs average optical power	155
4.65	The relationship between average illumination vs average SNR	156
4.66	The FOV effect vs maximum received optical power	157

4.67	Maximum optical power vs (a) effect of gain of concentrator (b) effectiveness of the refractive index of the lens at the photodiode	158
4.68	Maximum received optical power vs optical filter gain	158
4.69	Power contour distribution analysis at semi-angle 12.5° showed random points, (a) scenario 2 and (b) scenario 3	159
4.70	Received optical power at various points at optimum FOV (a) scenario 2 (b) scenario 3	160
4.71	Received optical power at various points at optimum Semi-angle (a) scenario 2 (b) scenario 3	160
4.72	The effect of varying the semi-angle value on the SNR of various data rates at the optimum FOV for both (a) Scenario 2 (b) Scenario 3	161
4.73	The effect of varying the FOV value on the SNR of various data rates at the optimum semi-angle for both (a) Scenario 2 and (b) Scenario 3	162
4.74	Side view of average SNR at optimum value semi-angle and FOV for (a) scenario 2 and (b) scenario 3	162
4.75	RMS distribution for scenario 2 at semi-angle 70° (a) at FOV 70° and (b) at optimum FOV	163
4.76	RMS distribution for scenario 2 at semi-angle 70° (a) at FOV 70° and (b) at optimum FOV	164
4.77	Validation of average RMS against various semi-angles	164
4.78	BER at a semi-angle of 12.5° for both (a) Scenario 2, (b) Scenario 3	165
4.79	BER vs semi-angle for both scenarios	166
4.80	Average BER side view distribution at semi-angle 50°	166
4.81	The BER for (a) side view validation between proposed scenarios and previous models (b) validation BER for the centre of the room	167
4.82	The relationship between average BER and mean luminance for (a) Scenario 2 and (b) Scenario 3	168
4.83	Illustrates a relationship between the average BER and the average optical power of (a) Scenario 2 (b) Scenario 3	168

LIST OF ABBREVIATIONS

A/D	-	Analog to Digital converter
ACO-OFDM	-	Asymmetric Optical OFDM
AFB	-	Analyses Filter bank
AlGaN	-	Aluminum Gallium Nitride
APD	-	Avalanche Photo Diode
ASK	-	amplitude-shift keying
AWGN	-	Additive White Gaussian Noise
B(k)	-	Transmitted Flip-FBMC signal
BER	-	Bit error rate
BW	-	Bandwidth
C	-	Speed of light
CAP	-	Carrier Amplitude and Phase
CIR	-	Channel Impulse Response
CO ₂	-	Carbon dioxide
CP	-	Cyclic Prefix
CV	-	Coefficient of Variation
D/A	-	Digital to Analog converter
DCO-OFDM	-	DC biased Optical OFDM
Ehor	-	Horizontal illumination
EMI	-	Electromagnetic Interference
EVM	-	Error Vector Magnitude
FBMC	-	Filter Bank Multicarrier
FFT	-	Fast Fourier Transformer
FOV	-	Field of View
GaN	-	Gallium Nitride
Gbps	-	Giga bit per second
IFFT	-	Inverse Fast Fourier transform

IM/DD	- Intensity modulation/direct detection
Im2ReC	- Imaginary to real converter
IMDR	- Imaging Diversity Receiver
InGaN	- Indium Gallium Nitride
IR	- Infrared
ISI	- Inter Symbol Interference
ISO	- International Organization for Standardization
IU	- Illumination Uniformity
LD	- Laser Diode
LED	- Light Emitting Diode
LoS	- Line of Sight
MCM	- Multicarrier Modulation
MRC	- Maximum Ratio Combining
NLoS	- Non-Line of Sight
NRZ	- Non-Return to Zero
NUP	- Non-uniformity power
OF	- Optimization Function
OFDM	- Orthogonal Frequency Division Multiplexing
OLED	- Organic Light Emitting Diode
OOK	- On-Off Key
OWC	- Optical Wireless Communication
P/S	- Parallel to Serial
PAM	- Pulse Amplitude Modulation
PAPR	- Peak Average Power Ratio
PC-LED	- Phosphor Converted LED
PD	- Photo Detector
PIN	- P-type semiconductor intrinsic semiconductor and n-type semiconductor
POF	- Plastic Optical Fiber
PPM	- Pulse Position modulation
PSD	- Power spectral density
QAM	- Quadrature Amplitude Modulation
RF	- Radio Frequency
RGB	- Red Green Blue

RYGB	- Red Yellow Green Blue
RZ	- Return to Zero
S/P	- Serial to Parallel
SCM	- Single Carrier modulation
SNR	- Signal to Noise Ratio
SSL	- Solid State Light
UV	- Ultra Violet
VLC	- Visible Light Communication
VLLC	- Visible Laser Light Communication
WDM	- Wave Division Multiplexing
WLED	- White Light Emitting Diode



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LIST OF SYMBOLS

μ -LED	- Micro Light Emitting Diode
I_o	- central intensity
I_ϕ	- light intensity at irradiance angle
λ	- wave length
$\phi_{1/2}$	- semiangle half power
v_o	- gab between subcarrier
τ_o	- time migration between real parts of symbol
$g_{(m,n)}$	- shifted version prototype filter
N_f	- leangth of synthesis
Φ	- luminous flux
Ω	- special angle
Φ_e	- energy flux
Λ_{\min}	- minimum sensitivity curve of PD
Λ_{\max}	- maximum sensitivity curve of PD
m	- lambertian emission
η	- Quantum efficiency
α	- Apsorption cofficiency
δ_{con}	- optical to electrical converter
ST	- speed transmission
fs	- sampling rate
n	- Refractive Index
nm	- Nano meter
PC -LED	- Phosphor Converted LED
rc -LED	- Resonant Cavity Light Emitting Diode
THz	- Tera hertz
MHz	- Mega Hertz
f	- Frequency

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	LIST OF PUBLICATIONS	191
B	DCO-FBMC MATLAB PROGRAM	192
C	FLIP-FBMC MATLAB PROGRAM	199
D	SENARIO 2 MATLAB PROGRAM	204
E	SENARIO 3 MATLAB PROGRAM	210
F	VITA	224



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CHAPTER 1

INTRODUCTION

1.1 Introduction

Extensive development in the utility of transportable electronic devices in the field of communications has increased the demand for high capacity data. Cisco Visual Networking Index Feb 2019 recently predicted an increase tenfold in mobile traffic over the following five years, during the same time duration forecast growth of mobile carriers by only 9%. It is also known that more communication and information exchange takes place inside indoor such as houses and offices, i.e., the percentage of these communications is 70% (Cisco, 2019), where Figure 1.1 shown the development of the smart device.



Figure 1.1: Smart device is used in the indoor environment
("Home Solution Wifi Devices Network Stock Photo - Download Image Now - iStock," 2011)

Figure 1.2 shows the growth in mobile traffic between 2017 and 2022, i.e., over five years, the global mobile data traffic rate in 2017 is 11.5 exabytes through a month in 2022, the data traffic is prospective an extent 77.49 exabytes a month annual growth of 47% (Bandwidth, Internet, Centers, & Market, 2022). Because of this rapid growth the spectrum of wireless communication may be saturation which in turn has led to bottlenecks in wireless carriers, and this requires the development of wireless communication model (Ergul, Dinc & Akan, 2015). To cop spectrum bottlenecks, choices are abundant including Optical Wireless Communications (OWC), comprising the three ranges of (UV), infrared (IR), visible light (Hany Elgala, Raed Mesleh, 2011).

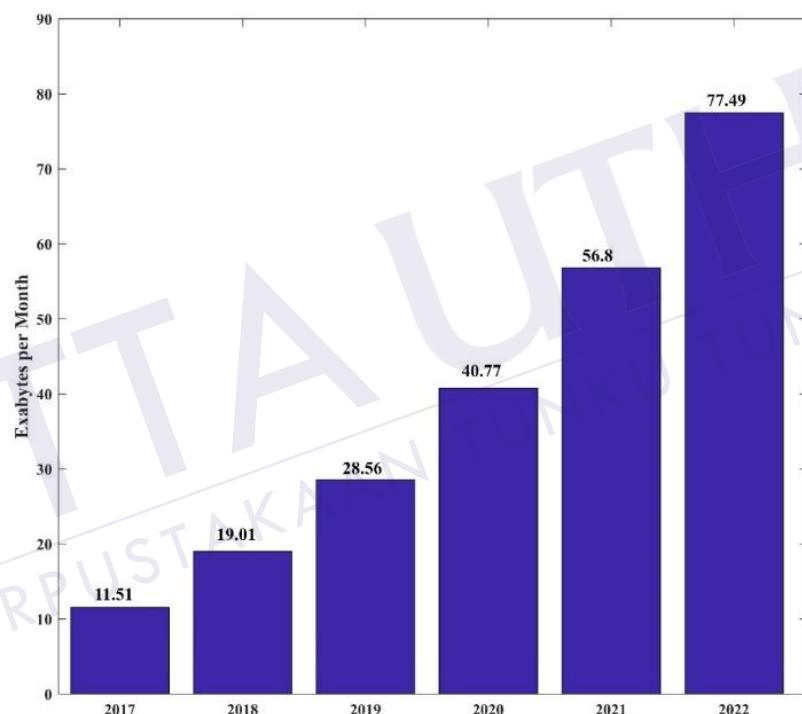


Figure 1.2: Global data traffic from 2017 to 2022 (in Exabytes per year) (“<https://www.statista.com/statistics/271405/global-mobile-data-traffic-forecast/>,” 2018).

One of the potential future communications networks is Visible Light Communication (VLC) which is complementary to radio-based wireless technologies based on radio frequency (RF) (Zafar, Bakaul, & Parthiban, 2017). VLC provides high speed given the light spectrum of the largest spectrum of the radio spectrum by 10000 times. VLC uses lighting fixtures that operate with solid-state light technology (SSL) (light-emitting diode (LED) or laser diode (LD)). SSL is the source of the most energy-

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