A MODELLING APPROACH OF 2D AND 3D CARRIERLESS AMPLITUDE PHASE MODULATION USING VCSEL IN ACCESS NETWORK TRANSMISSION SYSTEM

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Specially dedicated to my respected parents Markonah and Mohd Ridzuan,
my parents in law Norjanah and Sarkawi, my beloved husband Hafez,
my adorable children Aqeela, Ashraf, Arsyad, and Amsyar,
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ABSTRACT

Multi-dimensional carrierless amplitude and phase (CAP) modulation format is a high spectral efficiency modulation format, which allows realization of high order data modulation by employing a digital finite impulse response (FIR) filter with several taps to generate orthogonal waveforms. The reduction in system structure complexity makes CAP modulation format attractive and versatile since it requires relatively less computation and low implementation cost. However, experimental work is the most common practice when implementing the CAP signal using vertical cavity surface emitting laser (VCSEL) in optical transmission system. The experimental work may be constrained by several factors, for example, the availability or high cost of the intended equipment, limitation of time and lab usage, and logistic factor. The equipment and facilities also may affect the design as one cannot regulate or control the conditions as desired. Therefore, a 2D and 3D CAP modulation using VCSEL in access network transmission system is modelled via MATLAB program. The 2D and 3D CAP signal is transmitted using VCSEL through 20 km of single mode fiber (SMF) transmission. A bit error rate (BER) below a forward error correction (FEC) limit of 2.8×10^{-3} for error-free reception is obtained. Spectral efficiencies of 1.89 b/s/Hz and 1.33 b/s/Hz are reported for 2D-CAP-4 and 3D-CAP-4, respectively. The 2D-CAP-4 and 3D-CAP-4 performance using VCSEL for 20 km of SMF transmission is compared with the previous experimental works where the results show a 5.6 dB and 5.4 dB power penalty, respectively, hence prove the validity of the developed 2D and 3D CAP-VCSEL transmission system model for access network environment. This modelling graphically represents how things might look and helps to gain insight into which parameters are most important and significant to the system performance. As a result, this modelling can become a good alternative as it allows the understanding of the research work in an ideal setting and its potentially near-to-actual performance can be a guideline before the real-time implementation takes place.

ABSTRAK

Format pemodulatan amplitud dan fasa tanpa pembawa (CAP) dimensi tinggi adalah format pemodulatan spektrum kecekapan tinggi yang membolehkan pemodulatan data aras tinggi direalisasi melalui penapis sambutan dedenyut terhingga (FIR) beberapa tap bagi menjana gelombang ortogon. Pengurangan struktur sistem menjadikan format pemodulatan CAP menarik dan versatil kerana kurang pengiraan diperlukan disamping kos pelaksanaan rendah. Walau bagaimanapun, eksperimen adalah amalan yang paling biasa apabila melaksanakan isyarat CAP menggunakan laser pemancar permukaan rongga menegak (VCSEL) dalam sistem penghantaran optik. Eksperimen mungkin dikekang oleh beberapa faktor, contohnya, ketersediaan atau kos tinggi peralatan yang ingin digunakan, had masa dan penggunaan makmal, serta faktor logistik. Peralatan dan kemudahan juga boleh menjejaskan reka bentuk kerana seseorang tidak boleh menyelia atau mengawal keadaan seperti yang dikehendaki. Justeru itu, pemodulatan CAP 2D dan 3D menggunakan VCSEL dalam sistem penghantaran rangkaian capaian dimodelkan melalui program MATLAB. Isyarat CAP dihantar menggunakan VCSEL melalui penghantaran gentian mod tunggal (SMF) sejauh 20 km dan kadar ralat bit (BER) di bawah had pembetulan ralat hadapan (FEC) 2.8×10^{-3} untuk penerimaan tanpa ralat diperoleh. Kecekapan spektrum 1.89 b/s/Hz dan 1.33 b/s/Hz dilaporkan, masing-masing untuk 2D-CAP-4 dan 3D-CAP-4. Prestasi ini dibandingkan dengan eksperimen yang lalu, di mana keputusan menunjukkan penalti kuasa masing-masing adalah 5.6 dB dan 5.4 dB, sekaligus membuktikan pengesahan model sistem penghantaran CAP-VCSEL 2D dan 3D untuk persekitaran rangkaian capaian. Pemodelan ini mewakili rupa sesuatu dan membantu mendapatkan cerapan tentang parameter yang paling penting dan berkesan kepada prestasi sistem. Kesannya, pemodelan ini boleh menjadi alternatif yang baik kerana ia membolehkan pemahaman kerja penyelidikan dalam tetapan yang ideal dan prestasinya yang berpotensi hampir kepada sebenar boleh menjadi garis panduan sebelum pelaksanaan masa nyata berlaku.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

A	-	non-radiative surface or linear recombination coefficient
A_a	-	active area
A_{eff}	-	effective area of fiber evaluated as the area of the guided mode
α	-	attenuation of fiber
B	-	radiative bimolecular recombination coefficient
β	-	propagation constant of fiber
β_2	-	second-order differentiation of the propagation constant–group velocity dispersion (GVD)
β_3	-	third-order differentiation of the propagation constant–dispersion slope
β_{sp}	-	spontaneous emission factor
C	-	Auger recombination coefficient
c	-	velocity of light in vacuum
D	-	dispersion factor (unit = ps/nm/km)
D_M	-	material dispersion
D_W	-	waveguide dispersion
d_a	-	total thickness of the active layers
ε	-	gain compression factor
F_N	-	Langevin forces for the electron density
F_{N_p}	-	Langevin forces for the photon density
f	-	frequency
f_c	-	carrier frequency
g	-	material gain
g_p	-	peak gain coefficient

h	-	Plank's constant (h = 6.626×10^{-34} Js)
I	-	injection current
I_d	-	dark current of photodetector
I_p	-	photocurrent
I_s	-	shot noise current of photodetector
k_B	-	Boltzmann's constant (k_B=1.38×10^{-23} J/K)
L	-	length of optical fiber
M	-	number of symbols
N	-	carrier (electron or hole) density
N_p	-	photon density
N_t	-	transparency carrier density
η	-	quantum efficiency
η_e	-	extinction efficiency of the optical signal
η_i	-	current injection efficiency
η_o	-	optical efficiency
P	-	optical power
P_{out}	-	power of the optical signal out of the laser
P_{in}	-	incident optical power
q	-	electron charge ($q = 1.6 \times 10^{-19}$ C)
R	-	responsivity of the photodetector
R_s	-	series resistance
R_{th}	-	device thermal impedance
ξ	-	thermal conductivity of the material
T	-	symbol period
T_o	-	ambience temperature
T_s	-	symbol interval
τ_p	-	photon lifetime
τ_sp	-	spontaneous recombination lifetime
$\tau_\mathrm{sp,n}$	-	non-radiative lifetime
$\tau_\mathrm{sp,r}$	-	radiative lifetime
τ_{th}	-	thermal time constant
Γ	-	confinement factor

Γ_r	-	relative confinement factor
V_a	-	active volume
V_d	-	current-independent series voltage
V_p	-	volume of the laser cavity
V_s	-	ideal diode voltage
v	-	modulation frequency
v_r	-	resonance frequency
v_{gr}	-	group velocity
W	-	minimum bandwidth
γ	-	damping coefficient
ADC	-	analog to digital converter
ADSL	-	asymmetric digital subscriber line
AM	-	amplitude modulation
APD	-	avalanche photodiode
ASE	-	amplified spontaneous emission
ASK	-	amplitude shift keying
ATM	-	asynchronous transfer mode
AWGN	-	additive white Gaussian noise
B2B	-	back-to-back
BER	-	bit error rate
BPSK	-	binary phase shift keying
BS	-	base station
CAP	-	carrierless amplitude phase
CAP-VCSEL	-	carrierless amplitude phase-vertical cavity surface emitting laser
CCI	-	channel crosstalk
CD	-	chromatic dispersion
CDMA	-	code division multiple access
CMMA	-	cascaded multi-modulus algorithm
CO	-	central office
CP	-	cyclic prefix
CS	-	central site/station
CSRZ	-	carrier-suppressed return-to-zero

CW	-	continuous wave
CWDM	-	coarse wavelength division multiplexing
D8PSK	-	differential 8-ary phase shift keying
DAC	-	digital to analog converter
DBR	-	distributed Bragg reflector
DC	-	direct current
DCDM	-	duty cycle division multiplexing
DD-LMS	-	decision-directed least mean square
DEMUX	-	demultiplexer
DFB	-	distributed feedback
DFE	-	decision feedback equalization
DFT	-	discrete Fourier transform
DL	-	delay line
DML	-	direct modulation laser
DMT	-	discrete multitone
DM-VCSEL	-	directly modulated vertical cavity surface emitting laser
DPSK	-	differential phase shift keying
DQPSK	-	differential quadrature phase shift keying
DSG	-	digital signal generator
DSL	-	digital subscriber line
DSP	-	digital signal processing
DWDM	-	dense wavelength division multiplexing
EA	-	electro-absorption
EDFA	-	Erbium-doped fiber amplifier
EDGE	-	enhanced data GSM environment
EEL	-	edge emitting laser
ETDM	-	electronic time division multiplexing
EV-DO	-	evolution-data optimized
FDC	-	fiber distribution cabinet
FDM	-	frequency division multiplexing
FDP	-	fiber distribution point
FEC	-	forward error correction

FFE	-	feed forward equalization
FFT	-	fast Fourier transform
FIR	-	finite impulse response
FM	-	frequency modulation
FPGA	-	field programmable gate array
FSK	-	frequency shift keying
FTB	-	fiber termination box
FTTH	-	fiber to the home
FWM	-	four wave mixing
FWS	-	fiber wall socket
GPRS	-	general packet radio services
GSM	-	global system for mobiles
GVD	-	group velocity dispersion
HMB	-	hybrid multi-band
HSDPA	-	high-speed downlink packet access
HSPA	-	high-speed packet access
HSUPA	-	high-speed uplink packet access
IC	-	integrated circuit
IQ	-	in-phase quadrature
IEEE	-	Institute of Electrical and Electronics Engineers
IFFT	-	inverse fast Fourier transform
IM/DD	-	intensity modulation and direct detection
IoT	-	Internet of Things
IS-95	-	interim standard-95
ISI	-	intersymbol interference
ITU	-	International Telecommunications Union
LAN	-	local area networks
LD	-	laser diode
LED	-	light emitting diode
LO	-	local oscillator
LRM	-	long reach multimode
LTE-A	-	long term evolution-advanced
L/D	-	levels per dimension

M-PAM	-	*M*-ary pulse amplitude modulation
M-PSK	-	*M*-ary phase shift keying
M-QAM	-	*M*-ary quadrature amplitude modulation
MMF	-	multimode fiber
MM-VCSEL	-	multimode vertical cavity surface emitting laser
MUX	-	multiplexer
MZI	-	Mach-Zehnder interferometer
MZM	-	Mach-Zehnder modulator
NA	-	numerical aperture
NGAN	-	next generation access networks
NLSE	-	nonlinear Schröedinger equation
NRZ	-	non-return-to-zero
NRZ-TDM	-	non-return to zero-time division multiplexing
NZDSF	-	nonzero dispersion-shifted fiber
OA	-	optimization algorithm
OCS	-	optical carrier suppression
OCS-oDPSK	-	optical carrier suppressed-optical differential phase-shift keying
ODMA	-	orthogonal division multiple access
OFDM	-	orthogonal frequency division multiplexing
OFM	-	optical frequency multiplication
ONU	-	optical network unit
OOFDM	-	optical orthogonal frequency division multiplexing
OOK	-	on-off keying
OSSB	-	optical single-side band
OTDM	-	optical time division multiplexing
PAM	-	pulse amplitude modulation
PAPR	-	peak to average power ratio
PCM	-	pulse code modulation
PD	-	photodetector/photodiode
PDM	-	polarization division multiplexing

PIC	-	photonic integrated circuit
PIN	-	*p*-intrinsic-*n*
PLL	-	phase-locked loop
PM	-	phase modulation
POF	-	plastic/polymer optical fiber
PON	-	passive optical network
PR	-	perfect reconstruction
PRBS	-	pseudo-random bit sequence
PSK	-	phase shift keying
QAM	-	quadrature amplitude modulation
QPSK	-	quadrature phase shift keying
QW	-	quantum well
RAU	-	remote antenna unit
RF	-	radio frequency
RHD	-	remote heterodyne detection
RIN	-	relative intensity noise
RMS	-	root-mean-square
RoF	-	radio over fiber
ROP	-	received optical power
RRC	-	root raised cosine
RTI	-	real-time implementation
RZ	-	return-to-zero
SCM	-	subcarrier multiplexing
SDM	-	space division multiplexing
SE	-	spectral efficiency
SI-POF	-	step index polymer optical fibers
SM	-	spatial modulation
SMF	-	single mode fiber
SM-VCSEL	-	single mode vertical cavity surface emitting laser
SNR	-	signal-to-noise ratio
SPM	-	self-phase modulation
SRRC	-	square-root raised-cosine

SSB	-	single-side band
SSFM	-	split-step Fourier method
SSMF	-	standard single mode fiber
STBC	-	space–time block-coded
TDM	-	time division multiplexing
UMTS	-	universal mobile telecommunications system
VCSEL	-	vertical cavity surface emitting laser
VLC	-	visible light communication
VOA	-	variable optical attenuator
WDM	-	wavelength division multiplexing
Wi-Fi	-	wireless fidelity
WLAN	-	wireless local area network
WSN	-	wireless sensor networks
XPM	-	cross-phase modulation

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

The ever-increasing demand for high bandwidth capacity and high bit rate has revolutionized telecommunication-related technologies in general, most notably over the last few decades. Unlike before, users nowadays are always keen on fast internet communication, video-based multimedia, fast peer-to-peer file transfer, high-definition video streaming, online gaming, and many more. In addition, technological advancement in the telecommunication field allows for systems such as the Internet of Things (IoT) to become an inseparable component of modern living for most people. The tedious and repetitive tasks become much simpler and more organized via automatic actions and allow users to remotely monitor and manage their devices with an IoT system. However, the constant need for high-speed data rate put tremendous stress on the telecommunication system infrastructure in providing high-capacity link that can fulfil the wide IoT service requirements [1].

In order to ensure the telecommunication system infrastructure can support the high data capacity and rate that is typically required for the access network environment, the information transmission process should be continuous and perform extremely well. Conventional telecommunication access network infrastructures like twisted-pair telephony networks and coaxial cable networks seem to be having a difficult time dealing with traffic services issues. Due to the alarming network traffic issues, it has basically driven the migration of today's network access from conventional cable to optical fiber and broadband wireless systems [2]. Even though wireless communication provides seamless mobility, better security as well as reliability provided by optical fiber makes communication via wired lines preferable.

Generally, in communication systems, a by-product of bit rate–and-distance, *BL*, where *B* is the bit rate and *L* is the spacing of repeater, is commonly used to depict communication evolution. As shown in Figure 1.1, the *BL* product increased during the period of the emergence of new technologies, as marked by the red squares. As can be seen in the figure, telegraph technology has the least *BL* product whereas space-division multiplexing (SDM) has the most *BL* product associated with it. The notable increase in *BL* products occurs from around 1980 onward, when optical fibers technology was first introduced, thus marking the beginning of the usage of optical waves as the carrier. Optical communication systems employ high frequencies (~ 200 THz) in the near-infrared region of the electromagnetic spectrum, also called lightwave, as shown in Figure 1.2. Since lightwave systems used high carrier frequencies, the information capacity of optical communication systems is expected to be increased significantly.

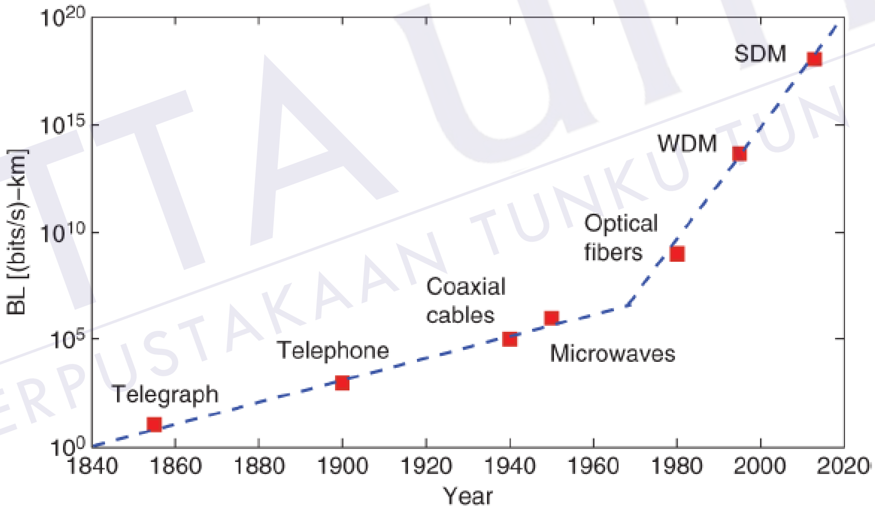

Figure 1.1: Bit rate–distance product, *BL* through technological advances [3].

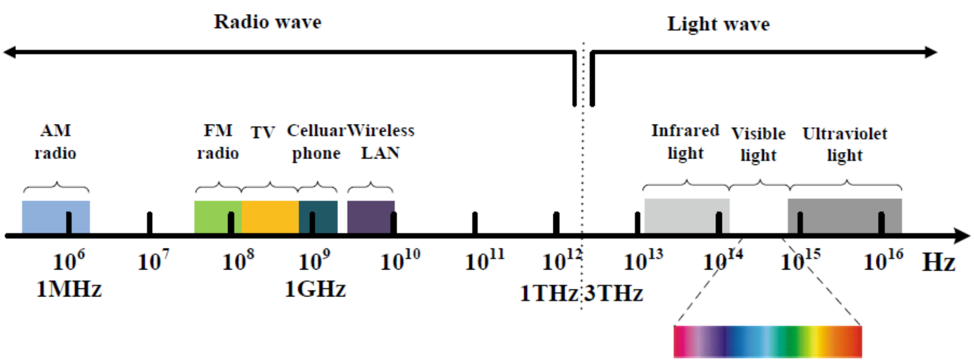

Figure 1.2: Electromagnetic spectrum [4].

Over the last few decades, fiber-optic communication technology and the corresponding network architectures and components, as well as groundbreaking communication system ideas are rapidly evolving. This also indirectly indicates that extensive research work in optical fiber communications and integrated optical electronics have taken place [5]. The optical fiber properties such as considerably large inherent bandwidth and low power loss make it a favorable option for high-speed and long-distance communication. Optical fiber provides the backbone of the broadband internet worldwide, conquers, and progressively becomes part of the access and in-home networks as depicted in Figure 1.3. The rapid deployment of optical fiber to the home (FTTH) and other access technologies promises the potential to deliver higher data rates to customer's homes. With rising demand for digital broadband communication, the optical communication network infrastructure is required to surpass certain characteristics in terms of bandwidth capacity, service subscribers, current fiber infrastructure, geographical layout, vendor requirements, available services and most of all, access methods for successful operation with wide connectivity.

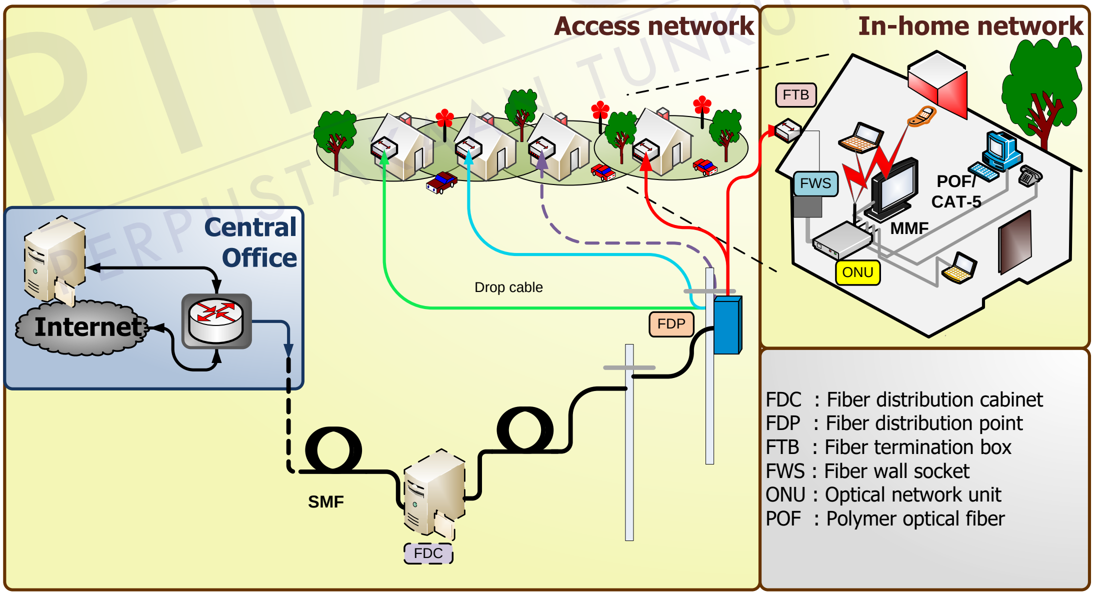

Figure 1.3: Optical communication access and in-home network from central office (CO) to customer premises supported with wired and wireless network [6].

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APPENDIX A

LIST OF PUBLICATIONS

Awards

1. Research & Innovation (RnI) Festival, Bronze, "2D-CAP Modulation for In-Home Network", M. B. Jaafar, M. B. Othman, N. M. Ridzuan, 2-3 November 2014, UTHM Johor.
2. Malaysia Technology Expo (MTE), Bronze, "High dimensionality CAP Modulation Technique for Access and In-Home Network", M. B. Othman, N. M. Ridzuan, M. B. Jaafar, M. F. L. Abdullah, J. B. Jensen, I. T. Monroy, 12-14 February 2015, PWTC KL.
3. 5th International Conference on Design and Concurrent Engineering (iDECON), Best Paper Award, "Comparison of CAP and QAM-DMT Modulation Format for In-Home Network Environment", N. M. Ridzuan, M. B. Othman, M. B. Jaafar, M. F. L. Abdullah, 19-20 September 2016, Langkawi Kedah.

Journals

1. N. M. Ridzuan, M. B. Othman, M. B. Jaafar, M. F. L. Abdullah, "Optical Transmission System Employing Carrierless Amplitude Phase (CAP) Modulation Format", *ARPN Journal of Engineering and Applied Science*, Vol. 11, No. 14, pp. 8776-8780, July 2016.
2. M. B. Jaafar, M. B. Othman, N. M. Ridzuan, M. F. L. Abdullah, "1.25 Gbps and 2.5 Gbps Data Rate Transmission of 2D-CAP Modulation for Access

Network", *ARPN Journal of Engineering and Applied Science*, Vol. 11, No. 8, pp. 5066-5070, April 2016.

3. N. M. Ridzuan, M. B. Othman, M. B. Jaafar, M. F. L. Abdullah, "Comparison of CAP and QAM-DMT Modulation Format for In-Home Network Environment", *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, Vol. 9, No. 3-2, pp. 1-4, Oct 2017.
4. N. M. Ridzuan, M. F. L. Abdullah, M. B. Othman, M. B. Jaafar, "Carrierless Amplitude Phase (CAP) Modulation Format: Perspective and Prospect for Next Generation Access Network (NGAN)", *International Journal of Electrical and Computer Engineering (IJECE)*, Vol. 8, No. 1, Sep 2017.

Conferences

1. N. M. Ridzuan, M. B. Othman, M. B. Jaafar, M. F. L. Abdullah, "Optical Transmission System Employing Carrierless Amplitude Phase (CAP) Modulation Format", *Malaysian Technical Universities Conference on Engineering and Technology (MUCET)*, 11-13 Oct 2015, Johor Bharu, Malaysia.
2. M. B. Jaafar, M. B. Othman, N. M. Ridzuan, M. F. L. Abdullah, "1.25 Gbps and 2.5 Gbps Data Rate Transmission of 2D-CAP Modulation for Access Network", *Malaysian Technical Universities Conference on Engineering and Technology (MUCET)*, 11-13 Oct 2015, Johor Bharu, Malaysia.
3. M. B. Jaafar, M. B. Othman, N. M. Ridzuan, M. F. L. Abdullah, R. Mohamad, T. Kanesan "Simulation of High Dimensionality Carrierless Amplitude Phase (CAP) Modulation Technique", *IEEE 6th International Conference on Photonics (ICP)*, 7510003, 14-16 March 2016, Kuching, Malaysia.
4. N. M. Ridzuan, M. B. Othman, M. B. Jaafar, M. F. L. Abdullah, "Comparison of CAP and QAM-DMT Modulation Format for In-Home Network Environment", *5th International Conference on Design and Concurrent Engineering (iDECON)*, 19-20 Sept 2016, Langkawi, Malaysia.

APPENDIX B

VITA

The author was born on September 15, 1984, in Batu Pahat, Johor, Malaysia. She went to Maktab Rendah Sains MARA, Muar, Johor, Malaysia for his secondary school. She pursued her degree at the Universiti Teknologi Malaysia (UTM) and graduated with the B.Eng. (Hons) in Electrical-Telecommunication in 2007. Upon graduation, she worked as an R&D Electrical Engineer at Panasonic Communication (Malaysia) Sdn.Bhd. for two years. She then worked as a Vocational Training Officer under Electrical & Electronics Department at Institut Latihan Perindustrian (ILP) Bukit Katil Melaka, Malaysia. While working, she enrolled at the Universiti Tun Hussein Onn Malaysia (UTHM), in 2011, where she was awarded the M. Eng. in Electrical Engineering in 2013. She attended the Centre for Graduate Studies of Universiti Tun Hussein Onn Malaysia (UTHM) and was admitted into the Ph.D. program in Electrical Engineering in 2014. In 2015, she followed her spouse to Kyoto Japan to further his study in Kyoto University for 3.5 years. Mrs. Noridah reported for duty as a Vocational Training Officer under Electrical & Electronics Department at Advanced Technology Training Centre (ADTEC) Melaka in 2019. She is currently a professional technologist of the Malaysia Board Technologists (MBOT) electrical & electronics technology (EE) and graduate engineer of the Board of Engineers Malaysia (BEM).

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