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CHARACTERIZATION OF SIGNAL TRANSMISSION OVER INTEGRATED SATELLITE AND LI-FI NETWORK FOR HIGH-SPEED RAIL ENVIRONMENT IN TROPICAL REGION

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By

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Malaysia High-speed railway (MyHSR) communications will become a key feature supported by intelligent transportation communication systems under the 4th Industrial Revolution for On-The-Move (OTM) internet access. Congestion in the radio spectrum, big data bandwidth networking issues and requirement of smaller antenna sizes simulating greater interest in the underutilized Ka frequency band. However, transmission at these shorter wavelengths is greatly influenced by signal noise resulting in signal attenuation and decreased link availability.

The main innovation is to improve the throughput and bandwidth load balancing between Ka-band High Throughput Satellite (HTS) space communication and heterogeneous hybrid Light Fidelity (Li-Fi) in tropic. In line with this, the objective is proposing of an approach of a Ka-band satellite signal attenuation expectation. The strategy also considering disabilities experienced during climate elements for tropical area and high portability situation on the High-Speed Rail (HSR) application.

The second part of the thesis compromises network integration, by enhancing the throughput and handover performance on both Satcom and Li-Fi. The process involves designing the indoor hybrid Li-Fi channel model where there is an exploration on the feasibility of utilizing a half breed HTS satellite and Li-Fi network for OTM application. In the third part, this thesis takes advance steps by focusing in achieving better satellite-Li-Fi backhaul network integration for both On-The-Pause and On-The-Move developments.

The methods focused on this approach, supported with a novel experimental, Proof of Concept (PoC) and validation of a heterogeneous satellite-Li-Fi network. This is done by managing the bandwidth and throughput capacity under the Deep Packet Inspection (DPI) model.

Finally, an analysis led, a reliable channel performance in tropical area for mobility application has been identify with an improvement of 19.52 % in overall receiving Packet Loss Ratio (PLR) including enhancement on the network throughput by 67.24% while carrying out DPI solution during unfavorable climate condition.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENCIRIAN UJIKAJI PENYIARAN ISYARAT KE ATAS RANGKAIAN SATELIT DAN LI-FI BAGI TREN KELAJUAN TINGGI DI KAWASAN TROPIKAL

Oleh

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Komunikasi Tren Berkelajuan Tinggi Malaysia (MyHSR) akan menjadi ciri utama yang disokong oleh sistem komunikasi pengangkutan pintar di bawah Revolusi Industri ke-4 bagi aplikasi penggunaan internet dalam system (OTM). Kesesakan spektrum radio, saiz data yang tinggi and jalur lebar berserta penggunaan antena piring yang lebih kecil menarik minat yang lebih besar pada jalur diatas frekuensi Ka. Namun, penularan penghantaran melalui medium gelombang yang lebih pendek sangat dipengaruhi oleh gangguan yang mengakibatkan pelemahan isyarat dan penurunan kebolehsediaan.

Inovasi utama penyelidikan adalah untuk mengekalkan kelajuan akses dan pengimbangan beban jalur lebar antara komunikasi ruang angkasa Ka-band Berkemampuan Jalur Tinggi (HTS) dan model saluran hibrid Li-Fi di kawasan tropika. Selaras dengan objektif, cadangan pendekatan strategi jangkaan pelemahan isyarat satelit Ka-band dengan mempertimbangkan kecacatan yang dialami semasa elemen iklim untuk kawasan tropika dan situasi mudah alih Kereta api Berkelajuan Tinggi (HSR).

Integrasi rangkaian, dengan meningkatkan penyaluran daya pemprosesan dan prestasi pada Satcom dan Li-Fi, mengambil bagian kedua dalam merancang model saluran Li-Fi hibrid dalaman. Bahagian ketiga tesis ini mengambil langkah awal dengan menumpukan pada pencapaian integrasi rangkaian penghantar hala balik satelit-Li-Fi yang lebih baik untuk Aplikasi Dalam Statik (OTP) dan Aplikasi Dalam Perjalanan (OTM).

Kaedah yang difokuskan dalam pendekatan ini, disokong dengan eksperimen novel, bukti terhadap konsep (PoC) dan pengesahan rangkaian heterogen

satelit-Li-Fi untuk membolehkan akses internet di mana-mana. Pemeriksaan Paket Dalaman (DPI) dilakukan bagi mengurus jalur lebar serta kapasiti daya pemprosesan yang tersedia.

Akhirnya, dalam analisis yang dipimpin, pelaksanaan pengalihan yang dapat di identifikasikan di kawasan tropika untuk aplikasi mobiliti telah dikaitkan dengan pengurangan hingga 19.52 % dalam keseluruhan penerimaan Nisbah Kehilangan Data (PLR) mengingat peningkatan untuk daya pemprosesan jaringan sebanyak 67.24% ketika melakukan pengaturan DPI pada saat iklim yang tidak menguntungkan keadaan.

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TABLE OF CONTENTS

			Page
ABSTRACT			i
ABSTRAK			iii
ACKNOWLEDGEMENTS			v
APPROVAL			vi
DECLARATION			viii
LIST OF TABLES			xiii
LIST OF FIGURES			xvi
LIST OF ABBREVIATIONS			xxii
LIST OF SYMBOLS			xxv
CHAPTER			
1	**INTRODUCTION**		1
	1.1	Research Motivation	2
	1.2	Problem Statement	3
	1.3	Objectives	4
	1.4	Research Scope	4
	1.5	Research Contributions	5
	1.6	Thesis Organization	6
	1.7	Chapter Summary	8
2	**LITERATURE REVIEW**		9
	2.1	HSR Communication Overview	10
	2.2	External Parameters Affecting Atmospheric Conditions	11
	2.3	Rain Attenuation Channel Model	12
	2.4	Satellite Signal Fading in Tropical Regions	13
	2.5	Mobility impairments	14
	2.6	Modulation and Coding Schemes	15
	2.7	Fade Mitigation Technique	15
	2.8	High Throughput Satellite	16
	2.9	Phased array antenna and characteristic	17
	2.10	OTM scenario of High-Speed Train	20
	2.11	Li-Fi communication overview	24
	2.12	Light Fidelity (Li-Fi)	24
		2.12.1 Basic Concept	24
	2.13	Li-Fi Cell Radius and Potential Coverage Interference	29
	2.14	Chapter Summary	32
3	**METHODOLOGY**		37
	3.1	Overall Research Work and Methodology	38
	3.2	Theoretical analysis	41

	3.3	Experimental measurement	42
	3.4	Measurements under rainy environment	46
	3.5	Analysis rain attenuation prediction.	47
	3.6	Measurements under non-rainy environment.	48
		3.6.1 Radio Frequency Interference survey.	48
	3.7	Measurements under rainy environment.	49
	3.8	HTS Communication Setup	51
	3.9	Link budget analysis for HTS channel at Ka-band	57
	3.10	Experimental setup for indoor Li-Fi communication	58
	3.11	One-Way Measurement Analysis	62
	3.12	Chapter Summary	63
4	**SATCOM RF NETWORK ANALYSIS**		64
	4.1	Atmospheric and transmission numerical analysis	65
	4.2	HTS Communication Antenna Compliance Setup Measurement	75
	4.3	One-Way Antenna Test Analysis and Performance	78
	4.4	OTP and OTM Experimental Analysis	82
		4.4.1 OTP Scenario	82
		4.4.2 OTM Scenario	84
	4.5	Signal Quality Analysis	91
	4.6	Chapter Summary	97
5	**LIFI NETWORK ANALYSIS**		98
	5.1	Analysis of HSR Indoor Li-Fi links	100
	5.2	Performance of Indoor Li-Fi links	104
	5.3	Li-Fi PER Performance Analysis	113
	5.4	Chapter Summary	116
6	**HETEROGENEOUS HYBRID SATCOM AND Li-Fi NETWORK ANALYSIS**		118
	6.1	OTM Measurement System and Scenario	120
		6.1.1 Handover Latency	120
	6.2	Atmospheric, Inbound and Outbound Measurement	122
	6.3	Analysing the ERL Rail Track Throughput Channel	126
	6.4	Electrical bridge, Inbound and Outbound measurement	128
	6.5	PER Analysis	130
	6.6	Chapter Summary	132

7	**CONCLUSION AND FUTURE RESEARCH RECOMMENDATION**	133
	7.1 Future Research Recommendation	133
	7.2 Original Contribution	134
REFERENCES		135
APPENDICES		145
BIODATA OF STUDENT		185
LIST OF PUBLICATIONS		186

LIST OF TABLES

Table		Page
1.1	Smart city functions under the 12th Malaysia	1
2.1	Technology Parameters Comparison Between Li-Fi, Wi-Fi, and the ethernet standards	9
2.2	Comparison of most common access network	9
2.3	Applied wireless technologies in railway systems	10
2.4	The comparison of different transponder	17
2.5	Comparison between satellite and Li-Fi throughput	27
2.6	Summary features for the Li-Fi, Wi-Fi WiMAX and Bluetooth	27
2.7	Shows estimated cell radius/diameter for a single AP at operating distances between 1.0 and 3.0 m	30
2.8	Extracts of literature for rain attenuation prediction	32
2.9	Extracts of literature for LSM model	34
2.10	Extracts of literature for hybrid Li-Fi communication	36
3.1	Characteristic of measurement sites	42
3.2	Characteristic measurement of other tropical countries	44
3.3	Precipitation measurement performance	45
3.4	Input parameters to the rain attenuation prediction model	47
3.5	Measurement scenarios	50
3.6	Measurement system parameters	55
3.7	Recorded duration	56
3.8	Recorded sample	56
3.9	Channel scenario probabilities	57
3.10	Characteristics of Li-Fi setup	59

3.11 Line of sight analysis and the propagation channel simulation 60

3.12 Responsivities from R/G/B to R/G/B 61

3.13 Li-Fi AP Measurement Parameter 62

4.1 Percentage error analysis for both Cy and Bj with ITU-R model 71

4.2 Rain attenuation at different satellites and transmission frequencies 73

4.3 Antenna summary of test result 76

4.4 Throughput test connection status 80

4.5 Lutz's Models' parameters calculation 91

5.1 Complete Li-Fi system parameter 102

5.2 Access point information 103

5.3 Li-Fi AP TX Driver information 103

5.4 UE USB dongle information 103

5.5 Characteristics of Li-Fi setup 107

5.6 Li-Fi AP interface information 107

5.7 Line of sight (LOS) analysis and the propagation channel measurement 110

5.8 Average measurement on UE 1 & UE 2 based on the LOS analysis scenario 112

6.1 Signal Propagation Delay 119

6.2 Signal condition summary 120

6.3 Results of handover initiation 121

6.4 HTS spot beam parameter 122

6.5 Outbound traffic from Teleport to the OTM array antenna 123

6.6 Inbound traffic from OTM array antenna to the Teleport 124

6.7 Traffic identifications result on with and without DPI algorithm 126

6.8 HSR communication performance 127

6.9 HSR communication performance before shielding mesh cage installed 128

6.10 HSR communication performance after shielding mesh cage installed 128

LIST OF FIGURES

Figure		Page
1.1	Proposed rail communications architecture for HSR	5
1.2	Brief methodology of study	7
2.1	Effect of weather and other physical effect on RF SatCom	11
2.2	Predicted rain attenuation for Malaysia, Singapore and India	13
2.3	Fast and slow fluctuations	14
2.4	(a) HTS satellite footprint (M5) vs. (b) FSS satellite footprint (M3)	17
2.5	Classification of planar Antenna	18
2.6	Dimension for (a) Phi (Φ), (b) Theta (Θ), (c) LPA (Ψ)	18
2.7	Guided feed wave against the array surface	19
2.8	(a) Electromagnetic induction effect (left picture) and (b) Electrostatic induction effect (right picture)	21
2.9	(a) Ground-current effect and (b) Metallic cross-conduction effect	22
2.10	Knife-edge diffraction concept	23
2.11	Block Diagram of a simple Li-Fi technology	25
2.12	2-D and 3-D views of LED source radiation patterns. (a) φ1/2 = 60◦. (b) φ1/2 = 40◦. (c) φ1/2 = 20◦.	26
2.13	APs deployed with no overlapping coverage	31
2.14	APs and STAs deployed under overlapping coverage and potential interference.	31
3.1	LOS and obstruction's scenarios in HSR communications	37
3.2	The overall summary of research work and methodology	38
3.3	The overall research work and methodology	39
3.4	Overall research work of heterogeneous link scenario	40

3.5	Overall measurement setup architecture of the OTM scenario	40
3.6	The methodology diagram of stationary scenario	41
3.7	Block diagram composites PAs + rain synthesizer of times series	41
3.8	Block diagram of measured attenuation PAs + simulated noise floor level	42
3.9	Local weather station measurements' equipment's	43
3.10	Display of real-time weather data for the rain intensity measurements	44
3.11	Ka-Band return downlink and on-site weather station logging setup	45
3.12	Received beacon signal captured from SA with Y and X-axis represent the received power level (dBm) and frequency (GHz) respectively	46
3.13	Rain intensity measurements obtained using (a) Vaisala RAINCAP® Sensor, (b) Casella Tipping Bucket Gauge	46
3.14	RFI test setup at trackside	48
3.15	Common mobility impairments	49
3.16	Measurement analysis ERL track route	49
3.17	The scenarios for high-speed train environment	50
3.18	SatCom connectivity on ERL network	51
3.19	Service network onboard train	52
3.20	Measurements equipment's setup	52
3.21	Antenna terminal configuration	53
3.22	Antenna terminal connection setup and different angle view	54
3.23	Measurement campaign ERL environments	56
3.24	Budget Calculator Screenshots for HTS satellite	58
3.25	Simplified Li-Fi communication setup	59
3.26	Li-Fi Setup of the connection on ERL	60

3.27 The architecture of Li-Fi system if using two AP for the analysis measurement 61

3.28 One-way connectivity setup 62

4.1 HTS OTM Satellite Network 64

4.2 Variation of 20.2 GHz signal level during a rain event 65

4.3 Variation of received signal availability during a rain event based on received antenna size 66

4.4 Comparison of the beacon attenuation signals of five antenna sizes for year 2019 at Cyberjaya. 66

4.5 Comparison of measured rain attenuation using an available model for Bukit Jalil in 2019 67

4.6 Comparison of measured rain attenuation using an available model for Cyberjaya in 2019 67

4.7 Measured attenuation from 2016 until 2020 until 2020 for both Cy and Bj 68

4.8 Measured rain intensity from 2016 until 2020 until 2020 for both Cy and Bj 69

4.9 Comparison of measurement with attenuation ITU-R model 69

4.10 Compared mean error for the two sites' attenuation in comparison with the prediction model for 2019 70

4.11 Compared mean error of the two sites' attenuation in comparison with the prediction model for 2019 and 2020 71

4.12 Observed temperature changes on March 23, 2019, at Cyberjaya 72

4.13 Rain attenuation at different θ and f 73

4.14 Relation between rain slant path length and elevation angle 74

4.15 Dry air and water vapor specific attenuation 75

4.16 Frequency Plot of the RX downlink with Test frequency of 8MHz Bandwidth 76

4.17 Frequency Plot of the RX downlink with ad-hoc transponder 77

4.18 Co-Pol signal measured within ITU-R S.580-5 77

4.19	OTM antenna patterns for different tilt angles	78
4.20	Measurement analysis ERL track route	79
4.21	One-way setup diagram	80
4.22	Screenshot from modem Odin F-50 router webpage	80
4.23	3G/LTE band cell mapper	81
4.24	LOS and common obstacles	82
4.25	Recorded attenuation data from an onsite tracking receiver at Bukit Jalil	83
4.26	Recorded attenuation data from an onsite tracking receiver at Cyberjaya	83
4.25	Electrical bridges and posts	84
4.26	Attenuation due to an electrical bridge	84
4.27	Typical overhead power line wire system	85
4.28	Electromagnetic induction from center of power line	86
4.29	Electromagnetic induction from center of power line with rail return path	87
4.30	Geometry of the Earth-Space RF Link meteorological stratiform precipitation conditions	88
4.31	Rain attenuation at different location within HSR rail route	89
4.32	*C/N* captured from the array antenna in Cyberjaya Dec-2019	89
4.33	Measured attenuation from the array antenna in Cyberjaya Dec-2019	90
4.34	*C/N* captured from the array antenna in Bukit Jalil Dec-2019	90
4.35	Measured attenuation from the array antenna in Bukit Jalil Dec-2019	91
4.36	Data recorded during the measurement campaign	92
4.37	Time series analysis based on signal performance	93
4.38	CDF vs. SNR effect based on (a) Power Arch and (b) Overall	94

4.39	PDF vs. SNR effect based on (a) Power Arch and (b) Overall	95
4.40	Signal analysis during measurement campaign	96
5.1	Typical physical layer system model of Li-Fi	98
5.2	Li-Fi noise source	99
5.3	Network structure of on-board Li-Fi network	100
5.4	Li-Fi indoor environment model	101
5.5	Received video capture on the laptop	101
5.6	Li-Fi bandwidth speed measurement via NetPerSec	102
5.7	Bidirectional and multiple access users. (a) 2-D model and (b) 3-D model	104
5.8	The responsivity of Li-Fi system for the measurement scenario	105
5.9	The architecture of Li-Fi system for the measurement scenario (a) side view (b) top view	106
5.10	Comparison of the received power based on calculation (via datasheet) and measurement results	108
5.11	Throughput over various distance with different type of UE LED	109
5.12	Pingplotter for the measurement of latency and packet loss	111
5.13	Average packet loss and average latency measured under the IrRed Wavelength	111
5.14	Wireshark analysis tool to capture the PER	114
5.15	Stationary user, Angle (θ) = 40o	114
5.16	Stationary user, Angle (θ) = 60o	115
5.17	Stationary user, Angle (θ) = 90o	115
6.1	Overview of experimental measurement for integrated satellite communications and Li-Fi network	118
6.2	SatCom RF and Li-Fi heterogenous network	119
6.3	ACM system solution	120

6.4 A latency test to AWS Singapore IP (46.137.255.254). 121

6.5 Ping test with round trip delay to AWS 121

6.6 Measured capacity under variable ACM on Feb 14th, 2020, at Bukit Jalil 123

6.7 Utilization recorded on Feb 14th, 2020, at Bukit Jalil for both Inbound (Red) and Outbound (Blue). 124

6.8 Carrier to Noise (C/N) recorded on Feb 14th, 2020, at Bukit Jalil 125

6.9 Cumulative distribution of rain intensity measured at Bukit Jalil 125

6.10 Display of attenuation and rain intensity during ERL day analysis 126

6.11 Packet Loss result for the ERL with different speed 127

6.12 Packet Loss result for the ERL with constant speed 127

6.13 Packet Loss result for the ERL during passing by the electric bridge 128

6.14 Carrier snapshot of spectrum analyzer when ERL during passing by (a) and after passing by the electric bridge 129

6.15 A shielding mesh cage installed at the multibeam to avoid EMI interference 129

6.16 (a) A shielding mesh cage installed on top of the array antenna which act as radome and (b) carrier snapshot after the shielding mesh cage installation. 130

6.17 Packet Loss result for the ERL during passing by the electric bridge after the after shielding mesh cage installed. 130

6.18 PER for different convolutional interleaves 131

6.19 PER for shielded vs non-shielded analysis 131

LIST OF ABBREVIATIONS

ACM	Adaptive coding modulation
AP	Access Point
APSK	Amplitude and phase-shift keying or asymmetric phase-shift keying
ASI	Adjacent Satellite Interference
BER	Bit Error Rate
Bj	Bukit Jalil
BSS	Broadcast satellite service
Cj	Cyberjaya
CMS	Carrier monitoring system
COWA	Centre on Optical Wireless Applications
DAH	Dissanayake Allnutt Haidara
DVB-RCS	Digital Video Broadcasting – Return Channel by Satellite
DVB-S	Digital Video Broadcasting – Satellite
DVB-S2	Digital Video Broadcasting – Satellite (Second Generation) Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications.
EIRP	Effective Isotopic Radiated Power
ERL	Express Rail Link Sdn. Bhd.
FMT	Fade Mitigation Technique
FSL	Forward service link
FSS	Fixed satellite service
FOV	Field of view
GEO	Geosynchronous Equatorial Orbit
GPIB	General purpose interface bus
GSM	Global System for Mobile Communications
GSM-R	Global System for Mobile Communications – Railway

HSR	High Speed Rail
HSR-S	High Speed Rail – Satellite
HTS	High throughput satellite
ICT	Information and communications technology
IoE	Internet of Everything
IoT	Internet of Things
ITU	International Telecommunication Union
Ka-Band	Kurz above band
Ku-Band	Kurz under band
LED	Light-emitting Diodes
Li-Fi	Light Fidelity (IEEE 802.11bb)
Li-Fi-C	Light Fidelity Communication
LMSC	Land Mobile Satellite Channel
LNA	Low-noise amplifier
LOS	Line of sight
LTE	Long Term Evolution
LTE-M	Long Term Evolution – Metro
LTE-R	Long Term Evolution – Railway
MB	Malaysia-Bukit Jalil
MC	Malaysia-Cyberjaya
MR	Malaysia-Rawang
M2H	Machine-to-Human communication
NBI	National Broadband Initiative
OBO	Output Back-Off
OLC	Optical Li-Fi communication
OOK	On-Off-Keying
OTM	On-the-Move
OTM	On the move

OTP	On the pause
PA	Power Arch
PAA	Phase Array Antenna
PoC	Proof of concept
QoE	Quality of Experience
QoS	Quality of Service
RF	Radio Frequency
RSL	Return service link
SA	Spectrum analyzer
SatCom	Satellite communication
STROC	Satellite-To-Tropics Channel
TETRA	Terrestrial Trunked Radio
UC	Ubiquitous Communication
UE	User Equipment
USB	Universal Serial Bus
VLC	Visible light communication
VSAT	Very small aperture terminal
VSAT	Very Small Aperture Terminal
WDM	Wave-length-division-multiplexing
Wi-Fi	Wireless Fidelity (IEEE 802.11a/b/g/n, 802.11ac and 802.11ax)
Wi-MAX	Worldwide Interoperability for Microwave Access (IEEE 802.16)
WLAN	Wireless Local Area Networks

LIST OF SYMBOLS

A_R	Rain attenuation
p	Percentage of exceedance time of the year
$R_{0.01}$	Rainfall rate at p = 0.01%
k	First rain specific coefficient
α	Second rain specific coefficient
Φ	Upper surface of the phase array antenna,
Θ	Scan angle
Ψ	Linear polarization angle
A_{cloud}	Cloud attenuation
RH	Relative humidity
σ_S	Standard deviation of the scintillation
A_{scint}	Scintillation fade depth
K	Rician factor
a	Amplitude of the direct signal
σ	Standard deviation
P_T	Power transmitted
G_T	Transmitter antenna gain
G_R	Receiver antenna gain
d	link distance
λ	Wavelength
L	Packet length
K_{mob}	Rician factor during clear LOS
K_{rain}	Rain impairment on Rician factor
L_A	Total atmospheric loss

L_{yy}	system losses
N	Noise power
c	The speed of light in vacuum
BW	Bandwidth
R_S	Symbol rate
R_C	Code rate
$y(t)$	Channel output signal
$x(t)$	Channel input signal
$f_{\mathrm{LM}}(t)$	Land Mobile Satellite channel fading
$n(t)$	Channel noise
$m(t)$	Mobility impairments
$s(t)$	tropospheric scintillation impairment
f_t	Total impairments
N_P	number of signal paths
$r(t)$	Envelope of the reflected signals
$A_i(t)$	Reflected power of the i^{th} signals
$\Gamma_i(t)$	coefficient related to angular Doppler frequency
ρ	Reflectivity of the walls
θ	Angle of incidence to the PDs
$\theta_{1/2}$	Half-intensity radiation angle
θ_{PD}	Maximal vertical orientation angle of Li-Fi receivers
ϕ	Angle of irradiation
Φ_0	Outage probability of user QoS
$\psi_\beta(x)$	β-proportional fairness utility function
Θ_F	Half angle of the receiver FOV

μ	User in HLRNs
χ	Refractive index in Li-Fi channel
$\gamma_{\mu,\alpha}$	Link data rate between user μ and AP α without handover considered
$\Gamma_{\mu,\alpha}(f)$	RF channel gain between user μ and RF AP *α*
$\tau_{p,ap}$	Packet processing time by the AP
$\tau_{p,cu}$	Packet processing time by the CU
$\tau_{q,ap}$	Packet queueing time in the AP buffer
$\tau_{q,cu}$	Packet queueing time in the CU buffer
$\pi_{\mu,\alpha}$	Payoff of user *μ* served by AP α in the EGT-based LB scheme
η	Average handover efficiency
η_b	Blockage density
η_{Los}	LOS Li-Fi channel gain
$\eta_{\mathrm{i}j}$	Handover efficiency from AP *i* to AP *j*
σ^2	Variance of the additive white Gaussian noise (AWGN)
$\mathcal{U}$	Set of users
u_α	Set of users that are served by AP *α*
T_X	Transmitter
R_x	Receiver
E_b/N_0	Energy per bit to noise spectral density ratio
E_J/N_0	Energy per symbol to noise spectral density ratio
f	Frequency
θ	Elevation angle
k	First rain specific coefficient
α	Second rain specific coefficient

γ_{Rann}	Rain specific attenuation
r_H	Horizontal reduction factor
P_H	Horizontal projection
L_S	Slant path length
H_R	Rain height above sea level
H_S	Earth station height above sea level
E_R	Earth radius
V_F	Vertical adjustment factor
$A_{0.01}$	Rain attenuation at p =0.01%
L_E	Effective rain path length
A_{Rain}	Rain attenuation
L_H	Rainfall horizontal path length
H_0	0°C isotherm height
p'	Crane's modified p
fr_{pri}	Principal relaxation frequency
fr_{sec}	Secondary relaxation frequency
T	Temperature
γ_{cioud}	Cloud specific attenuation
R	Rainfall rate
ε	Dielectric permittivity of water contents
β	fairness coefficient
ε_p	Amplification gains in Li-Fi systems
λ	Average user data rate (or packet) requirement
λ_μ	Data rate requirement for user μ
κ	Optical to electric conversion efficiency at the Li-Fi receivers

CHAPTER 1

INTRODUCTION

Malaysia is currently embarking towards smart cities by transforming to optimize the operation of the city for the better quality of life of the citizen. With the smart mobility for smart city policy objective under the 12th Malaysia Plan (2021 – 2025), which focuses on moving up the economic value chain by attractive Malaysia's position as global Multimedia and ICT Hub. This has been taken an example of the smart city for smart mobility around the world such as Amsterdam, Barcelona, Japan, and SongDo in South Korea. With this direction, expanding the communication network to guarantee more reasonable access to information and services, including reinforcing data information security [1]. Thus, supportive by the direction of the National Broadband Initiative (NBI) implementation, Malaysia, with its far and wide application of advance technologies such as fibre optics, wireless remote transmission, digitalization, and satellite services, has fabricated one of the more advanced telecom networks in the country. Malaysia has a national objective (Table 1.1) to see the country positioned as a developed country globally by the year 2050 [2].

With the burst in the development of the Internet and its usage in the most recent years (including during pandemic), individuals have much higher expectations of having the option to "ON" the Internet free of location/area. Towards smart city insights, rails and flights have been two areas where travellers have not ready to accomplish high-speed internet connections [3]. In the specific instance of trains, giving Internet access for on board travellers rails makes good business sense: Internet access for passengers can provide a revenue stream to the rail organization while pulling in more explorers.

Table 1.1: Smart city functions under the 12th Malaysia Plan [2]

Dimensions	Function/Aspects
Smart Mobility	To Increase the efficiency of public transportation, accessibility, mobility of people and traffic management through intelligent traffic management in the city. Aspects: • Efficient road accessibility • Efficient public transportation • Non-motorized accessibility • Availability of ICT infrastructure

For instance, a recent report in the United Kingdom found that 72% of business explorers were bound to utilize rails than vehicles or planes if Wireless Fidelity (Wi-Fi) access was accessible on rails or mobility service [3]. This study also found that 78% of these business travellers would utilize Wi-Fi access if it was made accessible on rails [1]. In the case of freight rails, Internet access can allow for real-time or close to real-time tracking of freight-related events onboard the rail, conceivably decrease in insurance premium to the freight carrier. In addition to these advantages, broadband internet access on rails can likewise improve the safety of the rail by allowing all control information handed over to the master control room which dispersed service can be monitored, validated, and controlled.

1.1 Research Motivation

The congestion of the radio spectrum band under Ku-band is stimulating greater interest in the Ka frequency band (beyond 18GHz). Transmission of these shorter wavelength can be greatly influenced by atmospheric effects, sometimes resulting in signal attenuation and decreased link availability for On-the-Move (OTM) application.

Signal and communication framework should work with extreme reliability under a wide scope of natural environmental conditions and should likewise withstand the interference effects produced by rail catenary power systems along the trackside. These systems are in generally large more unpredictable and expensive to be applied and maintain than those currently employed in nonelectrified dominion.

Although remote wireless providers are deploying additional access infrastructure by methods of new cells (5G) and Wi-Fi end points, the limitation is turning out to be overuse of existing radio frequency (RF) range. This shows as contention, interference, and results in an expansion in latency and a decrease in system throughput is expected. Additionally, in development nation, a “spectrum crunch” [1] is expected due to explosive growth in mobile communications. Again, when there are too many Wi-Fi users in the same area, the air band using which the signals are transmitted can get overloaded and keeps shifted in the frequency.

To mitigate this issue, new way to realize larger potential capacity at the wireless remote link are required and optical technologies including Light Fidelity (Li-Fi) are excellent candidates. Besides a thorough understanding of these phenomena is required to identify propagation limitations of this frequency band and compensate for them is system design and planning.

The research aspects and architecture take an advantage of both satellite networking and optical technology to implement a secure, reliable, and efficient network that meets today's requirements and provides the versatility to handle tomorrow's needs when network demand arise. Combining high throughput satellite (HTS) and Li-Fi is a new way of wireless communication that uses a Ka-band spot beam technology and light wavelength to transmit data wirelessly. Security would not be an issue as information data could not transfer without light. Thus, it can be used in high-security military areas where RF communication is prone to eavesdropping even cryptography is still being implemented.

1.2 Problem Statement

Ka-band HTS SatCom and Li-Fi has become an alternative technology to power the next generation of green wireless communications. However, the high attenuation of RF signals, Li-Fi technology complexities and implementation of the hybrid network are just exploited as a last resort or worst-case transport solution. Some key limitations of current platforms are the following:

- The existing multi-regions analysis lack to precisely extract a unique performance of the signal quality effects during extreme weather impairments in tropical region mainly under Ka-band frequency [3].

- Satellite communication link require higher antenna gain when 2-way satellites connectivity is used. Current analysis are more focuses on very small aperture terminal (VSAT) type application for rail communication under tropical region [4] and provides unsecure trainset running at 300 km/h.

- Most of high-speed railway (HSR) communications classify into two main fundamental classes: Indoor and Outdoor [3] and the integration of both network as a single access network is still questionable [4]. This may cause link unavailability and data transmission losses between these two environments, with an absence of a typical case study and real-time measurement under the tropical region.

- To the best of knowledge, real time link performance parameter analysis measurement for rail speed beyond than 100 km/h [4] is not available in Malaysia for HTS Ka-band and without the ability to understanding precisely how a specific signal will be impacted.

- Li-Fi is composed to overcome the crowded radio spectrum. However, initiative towards commercialise deployment are still lacking behind and provides no room for new network technologies, algorithms, protocols, and link quality assessment to be rapidly introduced. Additionally, its nature of visible light transmission, typical case study and a real-time deployment in indoor HSR communication is limited.

- Asymmetric channel: In the hybrid network system, the ratio of RF SatCom network to Li-Fi network throughput is ~ 1:40 [5]. Lack of well management network to determines that a specific line is congested without packet drop takes a different action, such as restricting some traffic.

In despite of those drawbacks, all the SatCom and Li-Fi communication domain specific constrains must be considered during real time link performance analysis.

1.3 Objective

The research aim is to achieve satellite to tropical land channel characterization and modelling for advanced technology on satellite communication systems that meet the dynamic of tropical weather conditions. More specifically, this research work will focus on below objectives.

1. To analyze and propose an analysis model that can be utilized for the Ka-band satellite signal attenuation prediction strategy for tropical area and high portability situation on the minimum quality of service of High-Speed Rail (HSR) communication.

2. To design, simulate and analyze the attainability of indoor Li-Fi channel model and its execution into handover in a heterogeneous HSR network.

3. To investigate, evaluate and validate the physical layer impacts towards OTM in real environments considering performance outcomes in the heterogeneous network and accuracy performance during handover using experimental measurements.

1.4 Research Scope

Next-generation Ka-band HTS, with added bandwidth, offers more choices for mobility industries such as HSR and OTM, which changes the way of legacy communication operates at. Due to the increase of usage of handhelds devices, this accelerates the demand on services of these devices in crowded places which have dramatically increased. Big data changes the way users access and demanding for cheap internet access solution. Conceivable numbers of Wi-Fi devices connected on the mobility system, create chances of interference with licensed bands networks, which threatens the safety and efficiency of mobility operations. A conceptual communication solution is designed to provide alternate offering in reducing the impact due to spectrum crunch. Solutions take advantage of both satellite networking and optical technology to implement a secure, reliable, and efficient network that meets today's requirements and provides the versatility to handle tomorrow's needs as they arise. This project is to stimulate and provide proof-of-concept (PoC) solution to ensure safe mobility operations by leveraging on Ka-band signal and the Li-Fi to ensure the users are always connected as shown in Figure 1.1.

Besides the research involves developing an alternative wireless technology in the contexts of satellite data broadcasting to help in realising the opportunistic benefits in bandwidth utilisation as well as providing fast and reliable wireless communications. Firstly, the feasibility study will be carried out on the Ka-band spot beam characteristic for mobility application comparing with the calculated margin. Secondly, the full model will be developed based on the Malaysian tropical weather condition. Finally, the entire set of communication design will be integrated with the new emerging technology, Li-Fi and experiments will be carried out in evaluating for closing the gap between theory and practice.

There is also growing concern about security with radio-communication. Radio provides a blanket cover, under which anyone could sneak. Unsecured or 'open' networks are an eavesdropper's paradise.

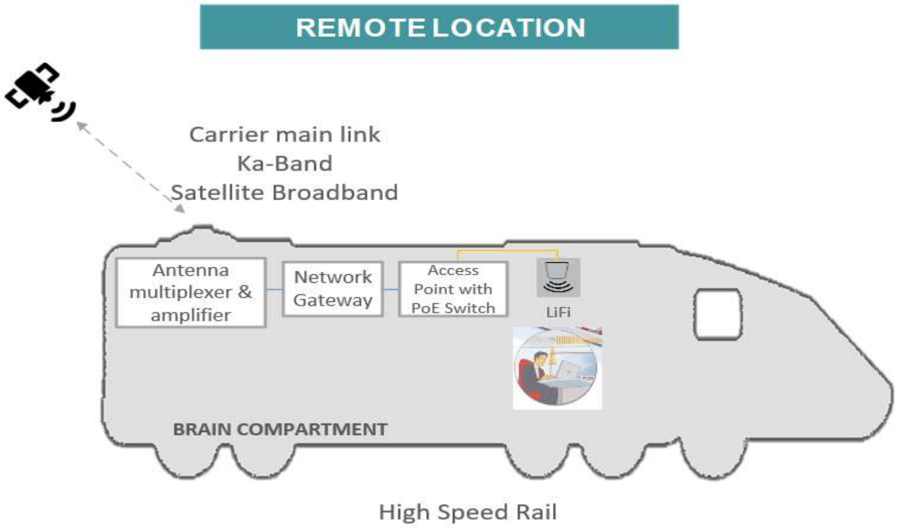

Figure 1.1: Proposed rail communications architecture for HSR

1.5 Research Contributions

The Research contributions are listed as follows:

- Investigate towards hybrid HTS Ka-band SatCom and Li-Fi network broadband connectivity under the tropical area with various weather conditions and different scenarios (e.g., power arch).
- Providing a reference benchmark towards network performance and its improvement in terms of throughput and latency which will potentially

benefit the fast passed online-gaming application under the OTM service.

- Faster implementation of HTS application comparing with complex terrestrial network under tropical geographical infrastructure is worth to be analyse and presenting new experimental measurement data for on-board Li-Fi.

1.6 Thesis Organization

The thesis is structured with seven chapters (summarized under Figure 1.2); where the current section presented on the channel modelling characteristics and drawbacks with the motivation of the study. Besides that, a detailed statement of the problems included, without limitation of research scope and study module. The aim of the research and the objectives, before ending with the research highlights with a list of main contributions are also briefed.

- Chapter 2 represent the literature review and its essential parameter involved in the study with a review of the previous works. This includes in depth analysis of the LMS channel characteristics towards the restrictions in the satellite transmission. The related background knowledge is firstly presented, including the fundamental concepts of an array antenna, HTS, Li-Fi networks, power line transmission and its impact towards radio frequency communications. It reviewed the literature that addressed SatCom and Li-Fi heterogeneous hybrid network with modelling for stationary and mobile terminals.

- Chapter 3 focused in the element of material and methods used including the field trials that performed in the research study. The later part of the methodology includes the channel analysis techniques, experimental measurements including link budget analysis for stationary and mobile terminals, channel modelling, and SatCom and Li-Fi quality indication.

- Chapter 4 address the framework design to qualify on the outdoor radio frequency under the high throughput satellite communication for HSR. This also discussed the implantation of one-way communication technique to extensively characterize the LMS and the limitations on the satellite transmission.

- Chapter 5 address the framework design to qualify on the indoor Li-Fi communication and includes an overview of the end-to-end system architecture implementation for HSR. In this chapter, also covers a well-known introduction to Li-Fi network, starting with a framework including the network structure, cell deployment, multiple access schemes, modulation techniques, illumination requirements and backhauling.

- Chapter 6 address the feasibility study on mobility management procedures via experimental proof of concept, mainly concentrating on handover under heterogenous hybrid satellite and Li-Fi network for ubiquitous internet access in a high-speed train environment. The drawback and availability of service is highlighted, and the corresponding modification to the heterogeneous SatCom and Li-Fi is discussed.
- In Chapter 7, the conclusions of the research work including achievement were made, highlighted the limitation, and recommended directions are introduced for future studies.

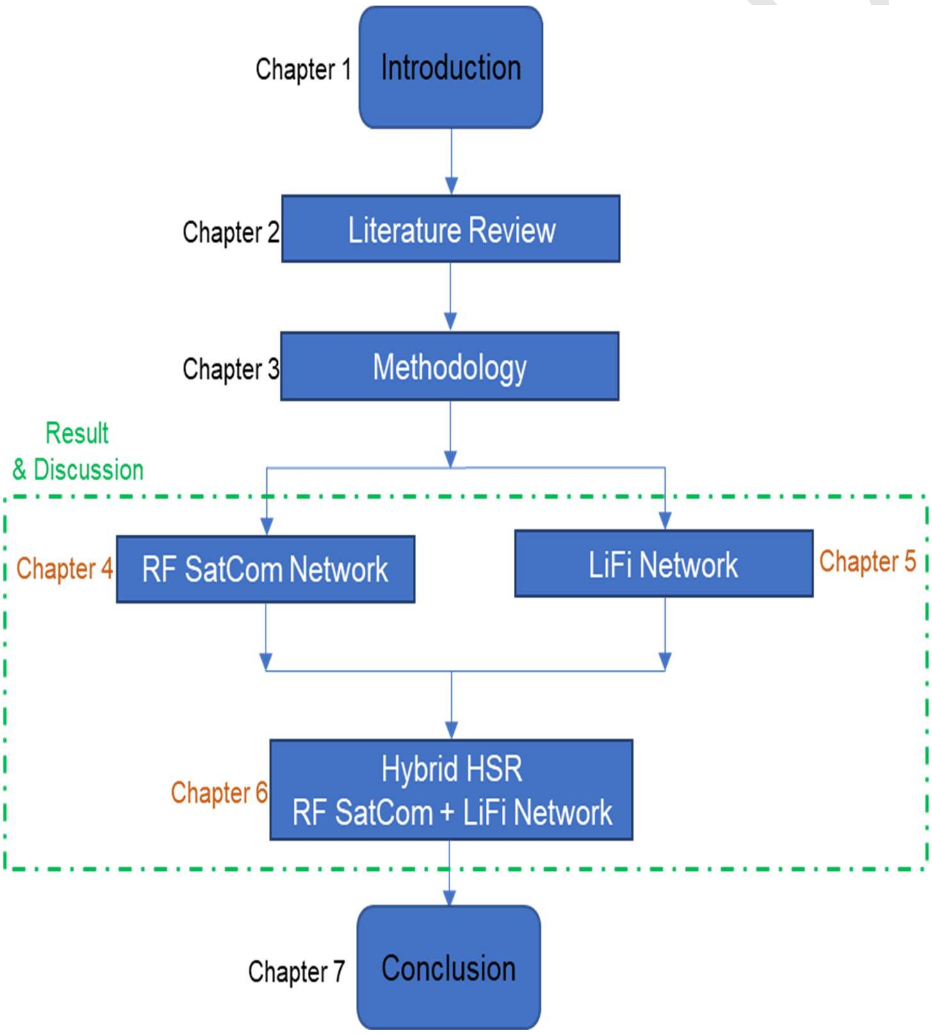

Figure 1.2: Brief methodology of study

1.7 Chapter Summary

The thesis is aimed to enlighten readers with the latest communication paradigm, Radio Frequency (RF) and Li-Fi along with OTM application in tropic region. As a potential key enabling technology in hybrid communication, OTM possesses a few key qualities to ensure its success mainly in Malaysia. However, certain aspect of OTM hybrid implementation in tropical region is not clearly stated, and potential problems may arise from the dynamic Internet of Everything (IoE) environment. Network heterogeneity and diverse application requirement from the high number of connected Internet of Things (IoT) devices demonstrated the need for improvement on the Layer-1 of hybrid network. Subsequently, the main aim and objective of the study are specified. Once the contributions of the study are clarified, the basic thesis outlined is given. In the upcoming chapter, a detailed discussion of hybrid communication, including network architecture and the main challenges will be provided for recommendation for future study.

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