AVAILABILITY MODELING OF TERRESTRIAL HYBRID FREE SPACE OPTICAL/RADIO FREQUENCY (FSO/RF) LINK UNDER TROPICAL CLIMATE CONDITION

BY

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ABSTRACT

Free-space optical (FSO) links provide gigabit per second data rates, but its availability can easily be affected by fading due to different meteorological conditions such as fog, haze, snow and rain. One of the feasible solutions to overcome this problem is to employ a Radio-Frequency (RF) as a complimentary link to the FSO to improve the link availability. Therefore, to mitigate the atmospheric effects on FSO link led to the development of hybrid FSO/RF systems. The performance of hybrid FSO/RF system is characterized by its link availability and high speed. Link availability consists of many factors including equipment reliability and other internal network design. However the factor which is very difficult to quantify is the fade statistics of atmospheric attenuation due to different weather conditions. Despite the licensed frequency bands, to achieve higher data rates in hybrid FSO/RF, higher frequencies for RF link are the most desirable to maintain high data rates comparable to the FSO link. In heavy rainfall regions, frequencies higher than 10 GHz are relatively sensitive to rain. A key issue in the deployment of hybrid FSO/RF in the tropical regions is the effects of rain on both FSO and RF links. Availability prediction of hybrid FSO/RF with the selection of suitable RF is an indispensable task, especially in tropical areas. Specific rain attenuation models namely, Carbonneau, Japan, Prague, Malaysia (KL) and Malaysia (Johor) proposed for FSO are investigated and a suitable one for the tropical areas is selected. Prediction methods for specific (dB/km) and longer path rain attenuation are available for RF, while only specific attenuation is available for FSO link. In this research, a total path rain attenuation prediction model for FSO is proposed based on effective path length models developed for microwave links. Rain intensity is measured with one-minute integration time at International Islamic University Malaysia (IIUM) campus for three years. Visibility data is also collected with one-hour basis at Subang airport in Kuala Lumpur for three years. Based on the measurements of rain rate, the percentage of time exceeding 0.01% level corresponds to nearly 100 mm/hr, while the highest of 168 mm/hr is observed at 0.000187%. Visibility ranged between 0.1 and 0.5 km under dense haze condition, while the lowest visibility observed as almost 2 km under normal haze condition. Fade margins for FSO and RF are investigated using measured rain intensity and visibility data. For 99.7% availability, FSO fade margin is varied from 6 dB to 31 dB over 1 km to 5 km links under normal haze; while fade margin is varied from 32 dB to 77 dB over 1 km to 5 km links for $\geq$ 99.999% under rain. Empirical models are also developed and proposed to predict the availability of FSO, RF, and hybrid FSO/RF links over path length ranges of up to 5 km. The RF availability prediction model is developed for frequency range from 10 GHz to 100 GHz using the ITU-R rain attenuation model. FSO availability prediction model is developed as a function of link distance and fade margin; while the RF availability prediction model depends on link distance, fade margin, and radio frequency. The proposed availability models can predict carrier as well as enterprise class availability. Comparison of the availabilities predicted by proposed models show good agreement with those based on tropical climate data and estimated by ITU-R.

خلاصة البحث

توفر تقنية الإتصالات البصرية اللاسلكية (FSO) سرعات تصل إلى ججابت للثانية الواحدة. ولكن توفر (Availability) موجات هذه التقنية قد يعرضها بسهولة إلى إنخفاض بسبب تأثرها بالعوامل المناخية مثل الضباب و الغبار الناتج عن التلوث و الثلوج والأمطار. أحد الحلول الممكنة لحل هذه المشكلة هي إستخدام موجات الراديو اللاسلكية (RF) لتكون مكملة للإتصالات البصرية اللاسلكية وبالتالي زيادة توفر الإتصال. تجنب الأحوال الجوية السيئة التي تأثر على كفاءة الإتصال للموجات البصرية أدى إلى إنتاج تقنية جديدة تدعى الإتصالات البصرية والراديو اللاسلكية الهجينة (Hybrid FSO/RF). هذه التقنية تعتبر من التقنيات الواعدة والتي تتميز بكفاءة عالية في الإتصالات اللاسلكية الأرضية المباشرة من نقطة إلى أخرى. جودة أدائها تتمثل في توفرها بسرعات عالية في الإتصال. عامل التوفر يتأثر بعدة عناصر منها الإعتمادية (Reliability) على الأجهزة وكيفية تصميمها وتصنيعها. من العوامل التي لايمكن التنبأ بها ومعرفتها أو إحصائها هي التقلبات المناخية طوال السنة نتيجة إختلاف الأجواء. بغض النظر عن شرط الحصول على تصريح أو دفع رسوم بالنسبة لنطاقات الراديو العالية، فان موجات الراديو العالية التردد هي الأنسب عند إستخدام تقنية الإتصالات البصرية والراديو اللاسلكية الهجينة وذلك لما توفره هذه الموجات العالية من سرعات إتصال تكون ملائمة لسرعات الإتصالات البصرية اللاسلكية. ولكن في المناطق التي تكون فيها الأمطار غزيرة مثل المناطق الإستوائية تكون موجات الراديو التي أعلى من 10 جيجا هرتز معرضة لمشاكل. لذا تكمن جوهر المشكلة في إستخدام تقنية الإتصالات البصرية والراديو اللاسلكية الهجينة في المناطق الإستوائية في مدى تأثر الموجات البصرية والراديو بالأمطار. إذا التنبأ بمعدل التوفر مع المرونة في إختيار موجات الراديو الأنسب وخصوصا في المناطق الإستوائية هو جزء مهم عند إستخدام هذه التقنية. لقد تم دراسة العلاقات الخاصة بحساب تأثير الأمطار لمسافة 1 كم فقط على الموجات البصرية وبناء عليه تم اختيار العلاقة الأنسب للمناطق الإستوائية. بالنسبة لموجات الراديو فان العلاقات الخاصة بحساب تأثير الأمطار إلى مسافة 1 كم و أكثر فإنها متوفرة، ولكن بالنسبة للموجات البصرية فهي متوفرة فقط إلى 1 كم. في هذا البحث، تم إشتقاق علاقة رياضية تقوم بحساب تقديري لتأثير الأمطار على تقنية الإتصالات البصرية إلى مسافات أطول من 1 كم. وأيضا تم تطوير علاقات رياضية للتنبأ بمعدل التوفر لتقنية الإتصالات البصرية والراديو و تقنية الإتصالات البصرية والراديو الهجينة بناء على قياسات لمعدل الأمطار والرؤية الأفقية لمدة ثلاث سنوات. لقد تم قياس معدل الأمطار في الجامعة الاسلامية العالمية بكوالالمبور، بينما تم قياس الرؤية الأفقية في مطار سبانج بكوالالمبور. علاقة المتاحية الخاصة بتقنية الراديو تم تطويرها لموجات راديو من 10 الى 100 جيجا هرتز باستخدام علاقات معتمدة من منظمة إتحاد الاتصالات العالمي(ITU-R).
بالنسبة لعلاقة التوفر الخاصة بتقنية الإتصالات البصرية اللاسلكية تعتمد على المسافه بين الإتصال والمعدل الإحتياطي للتأثيرات الجوية، بينما علاقة االتوفر الخاصة بتقنية الراديو تعتمد على المسافه بين الإتصال والمعدل الإحتياطي للتأثيرات الجوية وأيضا الموجة المستخدمة. أخيرا، تمت عمل مقارنات بين العلاقات الرياضية المقترحة مع معدلات التنبأ المتوفرة حاليا نتج عنه تقارب بين العلاقات المقترحة وبيانات التوفر المعتمدة.

APPROVAL PAGE

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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It is my utmost pleasure to dedicate this work to my dear mother (Fatimah), wife (Amanee) and daughters (Elaf & Joud), who granted me the gift of their unwavering belief in my ability to accomplish this goal: thank you for your support and patience.

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LIST OF ABBREVIATIONS

5G	5th Generation
BER	Bit Error Rate
CDF	Cumulative Distribution Function
Exabytes	500×one billion gigabytes
f	frequency
FSMC	Finite-State Markov Chain
FSO	Free Space Optics
GHz	GigaHertz
IR	Infrared Radiation
ISP	Internet Service Provider
ITU-R	International Telecommunication Union-Radio
LAN	Local Area Network
LASER	Light Amplification by Stimulated Emission of Radiation
LED	Light-Emitting Diodes
LOS	Line Of Sight
LWC	Liquid Water Content
MANETs	Mobile ad hoc Networks
MATLAB	Matrix laboratory
MIMO	Multiple Input Multiple Output
MMD	Malaysian Meteorological Department
MMW	Millimeter Wave

MODTRAN	Moderate Resolution Atmospheric Radiance and Transmittance Tool
N_2	Nitrogen molecules
NASA	National Aeronautics and Space Administration
O_2	Oxygen molecules
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
Rx	Receiver
SNR	Signal-to-Noise Ratio
SPSS	Software Program For Social Scientists
Tx	Transmitter
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

LIST OF SYMBOLS

mm	Millimetre
A	Link availability
Fm	Fade margin
mW	MilliWatt
dBm	Decibel miliwatt
θ	Divergence angle
mrad	Miliradian
A_r	Receiver aperture area
λ	Wavelength
nm	Nanometre
$Geom_{loss}$	Geometrical loss or attenuation
A_b	Area of the beam at distance d
D	Receiver capture diameter
π	Pi
d	Link distance
dB	Decibel
µm	Micrometer
I_d	Detected intensity at distance d
I_0	Initial launched intensity or power
σ	Scattering coefficient

r_o	Particles' radius size
n_i	Distribution of the *i*th particle
Q_i	Scattering efficiency of the *i*th particle
V	Visibility
ε	Contrast (visible) threshold
λ_o	Maximum spectrum of the solar band or visibility reference
q	Size distribution of the scattering particles
γ	Rain attenuation or extinction coefficient
Q	Extinction cross section
D_o	Drop diameter
$N(D_o)$	Complex refractive index of water *m*
γ_R	Specific rain attenuation
R	Rain intensity
k	Power law parameter
α	Power law parameter
mm/hr	Millimetre/hour
σ_R^2	*Rytov* variance
C_n^2	Refractive index structure parameter
$A_{0.01\%}$	Total path attenuation induced by rain for 0.01%
d_{eff}	Effective path length
r	Path length distance factor
A_p	Rain attenuation for other percentage of time *p*
R^2	Coefficient of determination

RMSE	Root Mean Square Error
CF	Curve Fitting
mm/min	Millimetre/minute
d_o	Equivalent rain cell
W	Water on the FSO transceiver window
r_1	Normalized path reduction factor
$r_{0.01\%}$	Reduction factor for 0.01%
$r_{(d,\%p)}$	Distance factor for all percentage of time
$A_{\%p}$	Total path rain attenuation for FSO at p percentage of a year
$P_{rain(\%p1)}$	Exceedance probability of rain at $\%p_1$
$P_{haze(\%p2)}$	Exceedance probability of haze at $\%p_2$
$P_{rain,haze(\%p)}$	Joint exceedance probability of rain and haze for a given fade in (dB)
$\partial\%$	Lowest exceedance probability that occur
e	Excess attenuation due to rainfall
LM	Link Margin
A_{Hybrid}	Link availability of hybrid FSO/RF
A_{FSO}	Link availability of FSO
A_{RF}	Link availability of RF
$P_{out,FSO}$	Outage probability of FSO
$P_{out,RF}$	Outage probability of RF
Fm_{FSO}	FSO fade margin
Fm_{RF}	RF fade margin

CHAPTER ONE

INTRODUCTION

1.1 OVERVIEW

At the early stage of human history, people used different tools to transmit messages through unguided transmission media over certain distances. They used visual signals through beacon fires, ship flags and smoke for communication purposes (Huurdeman, 2003). Ancient civilizations, such as Greeks and Romans used to transmit messages using their polished shields to reflect the sunlight during battles (Holzmann & Pehrson, 1995). In 1880, the first wireless telephone system 'photophone' was invented by Alexander Graham Bell (Phillipson, 2010). He used sunlight as a medium to transmit voice data over 213 meters with no wiring, and a solid state detector as the receiver that converted the light signal back into voice. The concept of Free Space Optics (FSO) started from the invention of photophone (Bouchet, Sizun, Boisrobert, & De Fornel, 2006). Free Space Optics is a wireless technology that uses light as a medium of transmission between transmitter and receiver (Kedar & Arnon, 2004). Currently, FSO systems are categorized under optical wireless technology (Uysal & Nouri, 2014). After the invention of laser, numerous scientists have conducted experiments to transmit different types of lasers using different modulation schemes (Goodwin, 1970). Bell Labs used ruby laser to communicate over 40 km (Hecht, 2009). Lightpointe is one of the most popular FSO commercial manufacturers. The chief scientist of Lightpointe developed the prototype for FSO system in Germany in the late 1960's (Lightpointe, 2009). Due to a large divergence of the propagated laser beams and nature conditions, FSO systems were able to operate over short distances. Transmitting optical laser in a confined medium will tackle the FSO distance limitations. In 1970's, fiber optic was invented and operates as a confined medium carrying light from one point to another at low cost. It became an alternative solution for optical transmission over long distances (Buck, 2004). Meanwhile, FSO continued to be developed by the military and NASA for military and space applications (Begley, 2002; Rabinovich et al., 2010). Over the last three decades, fiber optic infrastructure has expanded, covering most of the worldwide backbone networks. However, some of the areas are still challenging or it is not possible to install the fiber due to existing copper based network, wherein end users are unable to get access to the networks resulting in last mile "bottleneck" problem. In addition, scalability constraints of fiber installation cost and time, such as digging and permissions to lay fiber, make telecom service providers relook for feasible solutions (Sadiku, Musa, & Nelatury, 2016). Therefore, FSO systems start attracting attention as being a reasonable alternative solution to the last mile problem. Over the years, FSO technology has gained acceptance in telecommunication industry mostly in enterprise campus network. Thereby, FSO has become an emerging high speed point-to-point broadband technology.

FSO has many advantages such as (Khalighi & Uysal, 2014; Majumdar & Ricklin, 2010):

- Very High bandwidth which can support higher data rate,
- Easy to install where transmitter and receiver can be installed beside a window and within days,
- FSO systems, to date, have free licensing of frequency, above 300 GHz (Chan, 2006),
- Cost effectiveness compared to fiber optic,
- Very high security due to its narrow laser beams,

- Immune to electromagnetic interference due to different transmission windows that FSO used compared to RF.

The ultimate challenge facing FSO technology is that it can easily be affected by weather conditions such as fog and snow in temperate regions (Buckley, 2001; Flecker, Gebhart, Leitgeb, Muhammad, & Chlestil, 2006; Kalashnikova, Willebrand, & Mayhew, 2002; Willebrand & Ghuman, 2001) and rain in tropical regions (Zabidi, Islam, Al-Khateeb, & Naji, 2012). In addition to that, turbulence might be another factor affecting the FSO performance (Epple & Henniger, 2007; Raj, 2016; Ricklin & Davidson, 2002) .Thus, under the impact of adverse weather conditions, signal degradation may cause a link failure resulting in huge data lost. In order to compensate for the loss of data by ensuring efficient link availability performance, a comprehensive solution is needed. One of the solutions is to implement FSO link with a complementary RF link to create hybrid FSO/RF system. Thereby, the influences of different weather phenomena on the optical channel lead to the development of hybrid FSO/RF network. Hybrid FSO/RF system may enhance the performance of FSO system and optimize the link quality such as the availability performance of FSO link. Adopting hybrid FSO/RF link is a potential candidate to increase the link availability from enterprise class (> 99%) to carrier class (≥ 99.999%) compared to FSO link. Hybrid FSO/RF is a combination of two technologies, FSO and RF, in one system. Hybrid FSO/RF systems can be categorized under wireless communication technology as illustrated in Figure 1.1.

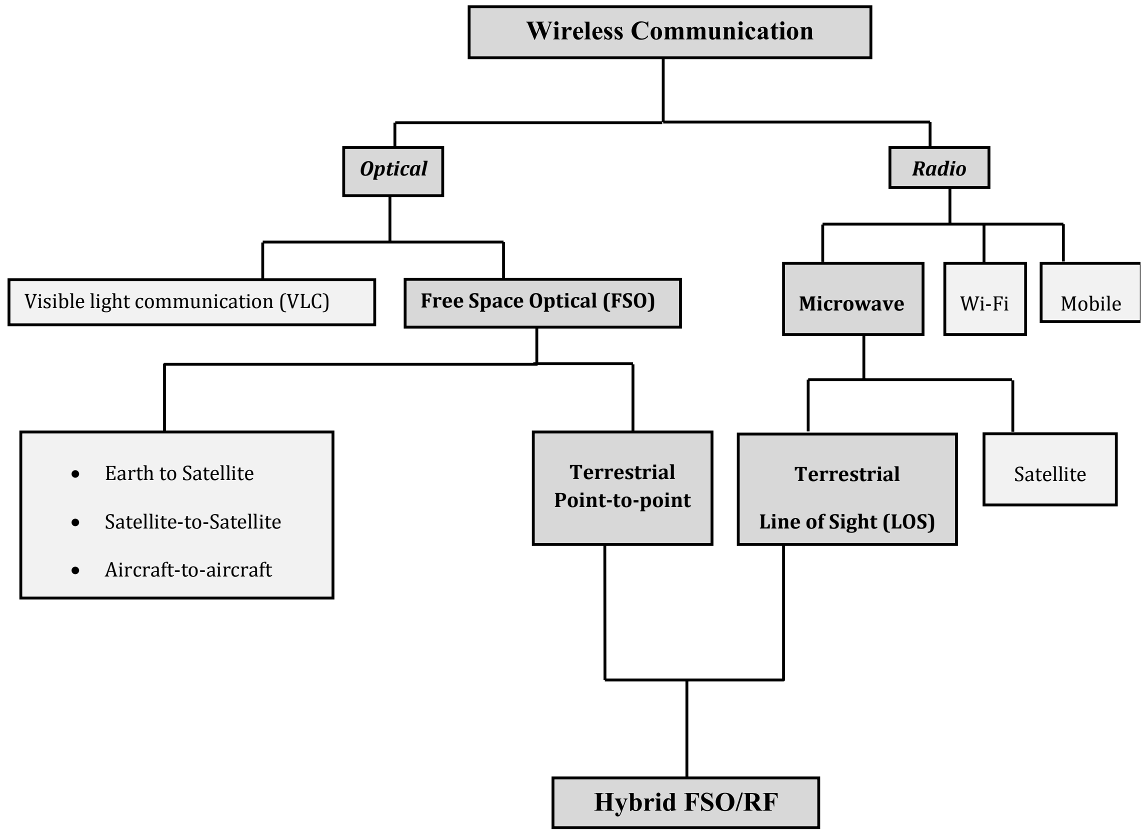

Figure 1.1 Categorization of Wireless Communications Based on the Research Scope

Hybrid FSO/RF systems consist of optical channel with a complementary RF channel and a switch or encoder that is used to distribute the data between both channels as illustrated in Figure 1.2.

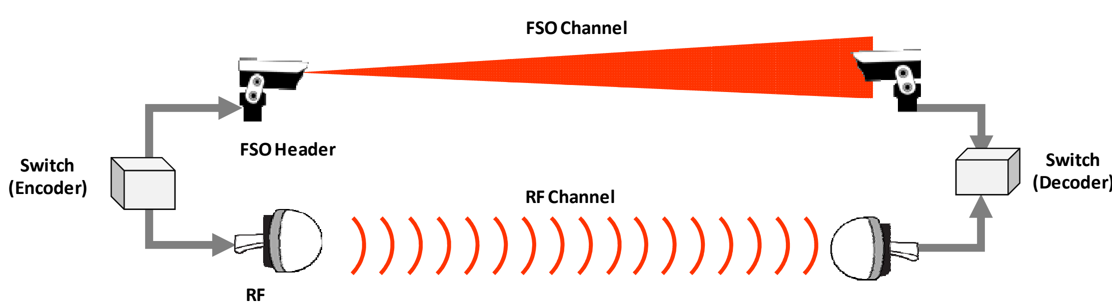

Figure 1.2 Hybrid FSO/RF System's Components