EMPIRICAL STAIRWELL PROPAGATION MODELS FOR LONG TERM EVOLUTION APPLICATIONS

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To my dearest parents, siblings, beloved wife and precious children, whose presence have been a constant enlightenment in my life

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ABSTRACT

This thesis presents investigation of path loss, *PL*, and shadowing, X_σ, of signal wave along and about multi floor stairways that have dog-leg stairwell configuration. The objective is to develop frequency-dependent empirical propagation models that could approximate *PL* and X_σ for two conditions. The first condition is when both transmitter, *Tx*, and receiver, *Rx*, are within the stairwell structure. The second condition is when either one of the *Tx* or *Rx* is inside adjacent rooms to the stairwells. Attention was also drawn towards the influence of stair flights and floor height to attenuation of signal wave as it propagates within the stairwell. Analysing the impact of the aforementioned structures within the stairwell, signal wave propagating between stairwell and adjacent in-building space as well as developing frequency-dependant empirical propagation model are research areas which have yet to be covered by previous propagation studies pertaining to multi floor stairway. Frequencies of interest, *f*, ranged from 0.7 GHz up to 2.5 GHz that cover various long term evolution (LTE) and public safety communication bands. Research works involved measurement campaign in four different multi-floor buildings inside Universiti Teknologi Malaysia's campus. *PL*'s relations with separation distance between *Tx* and *Rx*, *d*, and *f* were formulated with auxiliary site-specific terms added to improve two proposed empirical propagation models. It was found that for signal wave propagation where both *Tx* and *Rx* were within the stairwell, placing *Rx* at elevated or lower position than *Tx* does not influence significantly recorded *PL* data. However, for propagation between stairwell and adjacent rooms, placing *Rx* at elevated or lower than *Tx* may influence significantly recorded *PL* data. Suitable measurement campaign planning was arranged in the light of this finding. The proposed models were then examined and compared with ITU-R, COST and WINNER II indoor empirical propagation models. From measurement in dedicated testing sites, it was demonstrated that the proposed models have the smallest computed mean, μ_R, relative to the other standard models. The largest μ_R was -2.96 dB with a 3.34 dB standard deviation, σ_R. On the other hand, results from COST, ITU-R and WINNER II models demonstrated lower precision in all inspected settings, with the largest μ_R being 8.06 dB, 7.71 dB and 15.98 dB respectively and their σ_R being 3.79 dB, 6.82 dB and 9.40 dB accordingly. The results suggest that the proposed *PL* models, which considered the impact of building structures within and about the stairwell could provide higher *PL* prediction's accuracy for wireless communication planning pertaining to the stairwell environment, particularly for public safety responders.

ABSTRAK

Tesis ini mempersembahkan pemeriksaan terhadap kehilangan laluan, *PL*, dan pemudaran bayang, X_σ, gelombang isyarat di dalam dan sekitar tangga yang mempunyai konfigurasi separuh pusingan. Objektif penyelidikan ini adalah untuk menghasilkan model perambatan gelombang secara empirik yang bersandar frekuensi dan mampu meramal *PL* dan X_σ bagi dua keadaan. Keadaan pertama adalah ketika kedua-dua pemancar, *Tx*, dan penerima, *Rx*, berada di dalam struktur tangga. Manakala keadaan kedua pula adalah ketika salah satunya berada di dalam bilik-bilik bersebelahan dengan tangga. Tumpuan penyelidikan turut diberikan kepada kajian kesan deretan anak tangga dan ketinggian tingkat bangunan terhadap tahap pelemahan isyarat gelombang yang merambat di dalam struktur tangga. Analisis impak daripada struktur-struktur binaan tangga yang dinyatakan, kesan perambatan gelombang di antara tangga dan ruang dalam bangunan di sekitar tangga serta pembentukan model empirik perambatan gelombang yang bersandarkan frekuensi merupakan bidang kajian yang masih belum diterokai untuk kerja penyelidikan perambatan gelombang berkaitan tangga dalam bangunan bertingkat. Julat frekuensi, *f*, yang ditumpukan dalam penyelidikan ini adalah antara 0.7 GHz sehingga 2.5 GHz yang meliputi beberapa julat khusus untuk aplikasi evolusi jangka panjang (LTE) dan sistem telekomunikasi untuk tujuan keselamatan awam. Kerja-kerja pengukuran dilakukan untuk persekitaran tangga di dalam empat bangunan berbeza di kampus Universiti Teknologi Malaysia. Hubungan *PL* dengan jarak di antara *Tx* dan *Rx*, *d*, serta *f* kemudiannya diformulasikan. Beberapa terma tambahan ditambah pada formulasi yang telah dibentuk untuk menambahbaik dua model perambatan gelombang yang dikemukakan hasil analisis dalam penyelidikan ini. Bagi perambatan gelombang ketika *Tx* dan *Rx* berada dalam struktur tangga, didapati kedudukan *Rx* berada lebih tinggi atau rendah berbanding *Tx* tidak mempengaruhi secara signifikan data *PL* yang diperolehi. Namun, bagi perambatan gelombang di antara tangga dan bilik-bilik bersebelahan, kedudukan *Rx* yang berada lebih tinggi dari *Tx* boleh mengakibatkan data *PL* berbeza dengan ketara berbanding dengan keadaan kedudukan *Rx* lebih rendah dari *Tx*. Oleh itu, kempen pengukuran disesuaikan mengambil kira penemuan ini. Model-model perambatan gelombang yang dikemukakan kemudiannya diuji dan dibandingkan dengan model-model perambatan gelombang dalam bangunan ITU-R, COST dan WINNER II. Daripada penelitian yang dijalankan, dua model yang dikemukakan mempunyai min, μ_R, terkecil berbanding model-model rujukan lain. μ_R terbesar yang telah dikira adalah -2.96 dB dengan sisihan piawai, σ_R, 3.34 dB. Pengiraan berdasarkan model COST, ITU-R dan WINNER II pula menghasilkan kejituan yang lebih rendah bagi setiap pengujian yang dibuat, dengan μ_R terbesar boleh mencapai sehingga 8.06 dB, 7.71 dB dan 15.98 dB dengan σ_R sebesar 3.79 dB, 6.82 dB and 9.40 dB bagi ketiga-tiga model tersebut. Keputusan ini menunjukkan model-model *PL* dikemukakan yang telah mengambil kira impak struktur binaan di dalam dan sekitar tangga mampu meramal *PL* dengan lebih baik bagi perancangan sistem komunikasi wayarles persekitaran tangga, khasnya bagi kegunaan para petugas keselamatan awam.

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LIST OF SYMBOLS

PL	-	Path Loss
Γ	-	The Fresnel reflection coefficient
θ_i	-	Incident angles
θ_r	-	Reflection angles
E_i	-	Incident wave
E_r	-	Reflection wave
E_t	-	Transmitted wave
H_i	-	Incident wave magnetic field polarization
H_r	-	Reflection wave magnetic field polarization
ε	-	Permittivity
μ	-	Permeability
σ	-	Conductance
ε_r	-	Relative permittivity
f	-	Operating frequency
$\Gamma_{\parallel}$	-	Vertical E-field
$\Gamma_{\perp}$	-	Horizontal E-field
η	-	Intrinsic impedance of the mediums
θ_B	-	Brewster angle
λ	-	Operating frequency's wavelength

h_c	-	Critical height
h	-	Protuberance's height
ρ_s	-	Scattering loss factor
σ_h	-	Mean height
I_0	-	Zero-order of the first kind Bessel function
Tx	-	Transmitter
Rx	-	Receiver
v	-	Diffraction parameter
d_1	-	Actual earth-plane distance from transmitter to the edge causing diffraction
d_2	-	Actual earth-plane distance from receiver to the edge causing diffraction
d_1'	-	Modified earth-plane distance from transmitter to the edge causing diffraction
d_2'	-	Modified earth-plane distance from receiver to the edge causing diffraction
L_F	-	Free space loss
P_T	-	Transmitted signal power
P_R	-	Received signal power
G_B	-	Base station antenna's gain
G_M	-	Mobile antenna's gain
d	-	Distance between the transmitter's antenna and receiver's antenna
L_{ex}	-	Excess loss
L	-	Total Loss
d_0	-	Close-in reference distance
d_f	-	Fraunhofer distance

$\hat{n}$	-	Path loss exponent
$\hat{R}$	-	Residuals
X_σ	-	Shadowing model
σ_R	-	Standard deviation
μ_R	-	Normal distributed variable
PL_{FS}	-	Free space loss
α	-	Attenuation coefficient
k_f	-	Amount of floors
L_f	-	Floor loss
b	-	Non-linearity of PL increment with increasing floor
k_{wi}	-	Quantity of wall
L_{wi}	-	Type of wall
A	-	Fitting parameter
B	-	Intercept
C	-	Path loss frequency dependency
f_c	-	System frequency
X	-	Site-specific term related to the type of wall
FL	-	Floor Loss
N	-	Distance power loss coefficient
n	-	Number of floors
P_{tx}	-	Transmitted Power
G_{Tx}	-	Transmitted power of signal generator
G_{Rx}	-	Antenna gain at Rx-end
P_{Rx}	-	Received signal strength
$\hat{S}$	-	Total summation of the square of $\hat{R}$

$\hat{\beta}_0$	-	Intercept of the graph line
$\hat{\beta}_1$	-	Slope of the graph line
$\acute{C}$	-	Added constant term to power law expression
a & b	-	Constant terms in nonlinear regression expression
$\acute{n}$	-	Number of samples
$\bar{X}$	-	Mean of the samples
t_{crit}	-	Total number of samples
S	-	Standard deviation of the samples
$\bar{f}$	-	Optimum value
n_{mp}	-	Total measurement point
PL_p	-	Path Loss predicted
PL_m	-	Path Loss Measured
X_σ	-	Impact of shadowing
μ_R	-	Mean Error
σ_R	-	Standard deviation
$f(\hat{R})$	-	Probability Density Function curve
σ_X	-	Dispersion of variable population
μ_X	-	Mean of variable population
$\hat{Z}$	-	Maximum probability value that X_σ increases average PL
$\hat{T}$	-	A specific event in which the value 1 is yielded when it is true and 0 when it is false
$F(\hat{R})$	-	Normally-fitted Cumulative Distribution Function curve
$\widehat{F_n}(\hat{R})$	-	Empirical Cumulative Distribution Function curve
$\ddot{n}$	-	Number of $\hat{R}$ variables
PL_{d0}	-	Path loss at difference distance

$\hat{n}_{LOS}$	-	Path loss exponent for Line Of Sight
S1,..., S6	-	Stair flights 1 to 6
$FPF_{1\text{-}floor}$	-	One floor penetration factor
$FPF_{2\text{-}floors}$	-	Two floor penetration factor
E_{factor}	-	Even-numbered stair flight correctional factor
H_{factor}	-	High stair flight correctional factor
$\ddot{a},...,\ddot{d}$	-	Site-specific constant terms
$\hat{F}(\hat{R})$	-	Inverse- Cumulative Distribution Function curve
$\hat{n}_{closed\ range}$	-	Path loss exponent for closed range
AF	-	Attenuation based on number of separation floors
SW	-	Attenuation based on number of separation wall
n_w	-	Number of wall

LIST OF ABBREVIATIONS

IAN	-	Incident Area Network
4G	-	Fourth-Generation
CDF	-	Cumulative Distribution Function
CI	-	Confidence Interval
COST	-	Cooperation in the field of Scientific and Technical Research
FAF	-	Floor Attenuation Factor
FDTD	-	Finite Difference Time Domain
FPF	-	Floor Penetration Factor
GRG	-	Generalized Reduced Gradient
IAN	-	Incident Area Network
ITU	-	International Telecommunication Union
ITU-R	-	ITU's Radiocommunication Sector
LOS	-	Line Of Sight
LTE	-	Long Term Evolution
MIMO	-	Multiple-Input-Multiple-Output
PDF	-	Probability Density Function
QoS	-	Quality of Service
RF	-	Radio Frequency
TCFN	-	Temporary Cognitive Femtocell Network
UTM	-	Universiti Teknologi Malaysia
WAF	-	Wall Attenuation Factor

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CHAPTER 1

INTRODUCTION

1.1 Background

The success of public safety personnel's operations depend heavily on the ability of these personnel to communicate in the most effective manner. Critical information would need to be relayed among these personnel and to other associated parties that are involve in the emergency response. Growing investment towards improving the standards and capability of public safety communication technologies reflects the acknowledgement from public towards the need to equip public safety personnel with the finest telecommunication system and resources (Doumi *et al*., 2013). Many improvements to available communication technologies used for emergency response have been proposed in order to accelerate warning ability in the face of disaster and also assists in decision making in the disaster relief operations.

Among the most critical part of public safety communication is the one utilized by first responders who are present and actively engage in operations at emergency or disaster site. Contemporary emergency-response communication especially for first responders heavily depend on terrestrial cellular infrastructure. Unprecedented emergency events, either man-made or natural occurrence, could

lead to the cease of operation or inadequate service by terrestrial infrastructures due to damage or interrupted electricity supplies to those infrastructures. Thus, back-up telecommunication system has to be in place if such a disaster's aftermath happens (Portmann and Pirzada, 2008).

To improve the aforementioned limitations, deployment of incident area network (IAN) that could widen and improve radio frequency (RF) coverage has been studied and in the process to be made available. The IAN network can be set-up temporarily in an *ad-hoc* manner. IAN's areas of interests include all known environments where wireless signal strength reception need to be boosted up or the covered vicinity has to be extended (Gentile *et al.*, 2012).

The establishment of Long Term Evolution (LTE) and LTE-Advanced broadband technologies are expected to supplement variety of IAN requirements. Since these networks will be widely deployed, regulators, public community and manufacturers have begun cooperating towards realizing a common standard so less costly equipments can be used in facilitating LTE application for public safety use (Doumi *et al*., 2013). The use of carrier aggregation (CA) technology that is supported by LTE-Advanced system (Pedersen *et al.*, 2013) means that first responders could also take advantage of large data or files transfer for effective emergency response (Al-Hourani and Kandeepan, 2013). Therefore, investigating frequency range covering from below 1 GHz until beyond 2 GHz (Yan *et al.*, 2013) that have been allocated for LTE or LTE-Advanced applications should be important to strengthen the know-how in implementing LTE- assisted IAN.

In a high rise where the number of floors is considerably large, the availability of reliable telecommunication means for emergency responders inside stairway is crucial. These responders commonly use the stair when attending to emergency cases that take place in a multi floor building due to safety reason. Thus, radio propagation along the stairway need to be carefully characterize in

order to ensure communication link between emergency responders is not susceptible to interference due to the stair setting (Lim *et al.*, 2009). Given that the stair structure is heavily made up of reinforced concrete (Ashraf *et al.*, 2010), radio frequency penetration from outside sources is typically minimized (Aerts *et al.*, 2013). Thus, the use of repeaters or relays to extend coverage should be expected (Craighead, 2009). Small cell LTE relays could play important roles in filling up the gap towards enhancing public safety communication coverage for this crucial segment of a multi floor building (Al-Hourani and Kandeepan, 2013).

An IAN that is set up to provide reliable wireless coverage for stairways in a tall high rise would require a significant number of relays. Relays may need to be placed within the stair itself (Souryal *et al.*, 2008) as well as in nearby indoor locations (Liu *et al.*, 2014). The planning stage of establishing the relay-assisted IAN is very critical. Deploying too many relays can cause conflict in the network due to packet loss and time delay (Rafaei *et al.*, 2008). On the other hand, insufficient number of relays would results in poor coverage (Liu *et al.*, 2014). Modelling signal attenuation or popularly known as path loss, *PL*, as a function of separation distance between transmitter-receiver link could help by providing early *PL* prediction and act as a tool to demonstrate best practices when setting up the wireless network (Valcarce and Zhang, 2010).

1.2 Problem Statement

Investigation on wireless signal wave propagation along the stairway at different operating frequency ranges had been carried out by Yang and Wu (2001), Teh and Chuah (2005) and Lim *et al.* (2009). The research works, nevertheless, were based on ray-tracing deterministic approaches that are computationally intensive and require prolonged time-period to complete. Additionally, the laborious tasks require the use of software with complex

computational capabilities. A much simpler and easily implemented technique to estimate signal wave's attenuation is via empirical *PL* model (Valcarce and Zhang, 2010). Empirical *PL* models for the stairway environment were presented by Yu *et al.* (2014), Lim *et al.* (2014) and Wang *et al.* (2014) but only covered operating frequency for 2.4 GHz and higher frequency ranges.

To the author's knowledge, no existing stairway's empirical *PL* models for spectrum range below 2 GHz have been proposed and available in the literature despite various bands in the mentioned range have been stipulated for public safety purpose (Matolak *et al.*, 2013). Therefore, developing comprehensive empirical *PL* model that comprise of frequency spectrum below 2 GHz is necessity to assist stairway's IAN planning since unprecedented emergency events may require the IAN to be adaptive and operates in more than one frequency (Rafaei *et al.*, 2008).

For better characterisation of signal wave attenuation inside multi floor buildings, a mathematical term is commonly introduced in empirical *PL* formulation to signify losses incurred as signal wave penetrates into different floors (Sarkar *et al.*, 2003). The proposed stairway's empirical *PL* models by Yu *et al.* (2014), Lim *et al.* (2014) and Wang *et al.* (2014) had not considered the floor attenuation factor, which limits practical application of the models given the ambiguity on the maximum floors that the models can still be considered befitting. Hence, a different independent analysis need to be carried out to identify the floor attenuation factor for better stairway's *PL* prediction.

It is also important to note that attenuation of signal wave as it penetrates nearby floors could be influenced by building's floor height. Investigation to demonstrate the dependency of signal wave losses to floor height can improve indoor *PL* model (EUR., 1999). Emergency responders may encounter different high rises with floor height variations and need unique strategies to deploy IAN's relays based on the different heights. Investigation on the effect of floor height to

floor attenuation is thus essential and must be looked into in order to warrant that proposed *PL* model for the stairway setting could be fine-tuned with respect to diverse building floor height. At present, no study has been carried out to characterise the effect.

Aforementioned studies on signal wave propagation were also limited to propagation along the stairway structure and did not consider neighbouring indoor setting. IANs for stairway coverage are in fact expected to include adjacent in-building space where emergency responders demand seamless connectivity beyond the stairway to support reliable communication in their emergency operations (Souryal *et al.*, 2008). Signal wave's propagation through the stairway into nearby multi floor sections may have traits that can be distinguished from propagation in conventional indoor settings (Austin *et al.*, 2011). Modelling the setting would facilitate future IAN implementation through an optimized deployment strategy (Liu *et al.*, 2014).

1.3 Objectives

The aim of this research was to develop empirical propagation models with respect to the stair environment based on measured *PL* along and about stairways residing in multi floor buildings. This aim was meant to support and further enrich literature on LTE application for public safety communication. Thus, objectives that were included in this research study are as follows.

1. To characterise *PL* and the shadowing phenomena for propagation within the stairway as well as between the stairway and adjacent indoor settings.

2. To conduct the characterisation of *PL* and shadowing at different operating frequencies within the spectrum allocated for LTE.

3. To develop frequency-dependent empirical propagation models for the investigated scenarios based on the characterisation of *PL* and shadowing conducted.

4. To validate the empirical propagation models with measurement results and make comparison to available indoor empirical propagation models.

1.4 Scopes of Work and Research Limitation

In order to ensure the research study's significance, the most popular and generally constructed stairway arrangement in multi floor buildings will be investigated. Follows, are the scopes of work decided for this research study.

1. The study of *PL* and shadowing focused on signal wave propagation within and about reinforced concrete dog-leg stairway environment.

2. The study of *PL* and shadowing between stairway and nearby setting would be limited to neighbouring rooms adjacent to the stairway.

3. Empirical *PL* measurement carried out at five narrow band frequencies namely 0.7 GHz, 0.9 GHz, 1.8 GHz, 2.1 GHz and 2.5 GHz.

4. Measurement carried out at four different student residential and faculty buildings inside Universiti Teknologi Malaysia's (UTM) campus with diverse floor height.

5. Measurement carried out in the presence of sporadic and small number of moving stair occupants.

1.5 Research Contributions

This research work focused on modelling *PL* empirically with respect to the dog-leg stairwell, which is the most common stair configuration found in modern buildings. The proposed *PL* models have been validated and are shown to compute closer prediction-to-measured *PL* values relative to several indoor *PL* models that are usually set as benchmark when assessing indoor signal wave attenuation (Zyoud *et al.*, 2013). Spectral range covered by the proposed frequency-dependant *PL* models envelop bands that have been dedicated for public safety communications (Matolak *et al.*, 2013) as well as Long Term Evolution (LTE) fourth-generation (4G) wireless technology (Yan *et al.*, 2013). The proposed models could therefore be used as reference works for not only public safety communication but also the planning of LTE indoor small cells for frequencies within the range where wireless coverage associated to multi floor stairwell is concerned (Lim *et al.*, 2014). Follows are the contributions pertaining to indoor empirical propagation modelling presented from this research study.

1. The reference measurement campaign setup for transmitter, *Tx*, and receiver, *Rx*, positioning at two examined scenarios, namely when both *Tx* and *Rx* are within the stairwell structure as well as when either one is located outside and adjacent to the stairwell structure. Another related contribution for the latter scenario include the identification of region where different locations of receiver, *Rx*, but with approximately similar *d* could nonetheless resulted in considerable differences in terms of *PL* values due to their relative position to *Tx*. The observation was reflected in the proposed model.

2. The development of the first frequency-dependant *PL* and shadowing models, covering a nearly 2 GHz wide spectrum ranging from 0.7 GHz up to 2.5 GHz for within the stairwell scenario.

3. The description of floor loss and stair flight impact to wireless signal wave attenuation that have never been included in preceding works on stairwell's empirical *PL* models. Results from examining signal wave attenuation when penetrating different floors had in addition revealed the influence of floor height variations to *PL*. These observations have been weighed in to develop a more accurate empirical *PL* model for propagation along the stairwell scenario.

4. The development of the first frequency-dependant *PL* model for stairwell and nearby in-building setting covering spectrum ranging from 0.9 GHz up to 2.5 GHz. Experimental works and analysis on *PL* for stairwell and adjacent rooms in this research work have produced frequency-dependent *PL* model that is more precise for the examined scenario relative to standard indoor empirical models.

1.6 Thesis Layout

The next five chapters in this thesis cover the fundamentals along with research activities involved in the development of propagation models along and about the multi floor stairwell for LTE frequency spectrum plus the inferences drawn from the study.

The second chapter is the literature review. This chapter provides review on recent developments of public safety communication along with technologies that have been proposed to enhance the communication system. Next, studies

carried out by researchers on wireless signal wave propagation along the stairway are described. Topics on wireless propagation and the stairway structure are then explained. The chapter subsequently presents the fundamentals of statistical analysis employed in this investigation work.

The third chapter is on methodology. This chapter illuminates the flow of research study by explaining procedures of research activities that have taken place. The activities include pilot study, measurement campaign, and using certain techniques to analyse collected data for the development of propagation model.

Chapter four is on results and discussions for propagation along the stairway. In this chapter, results and analysis based on recorded *PL* data for the stated scenario are presented in order to demonstrate related *PL* and shadowing models as well as their validation.

Chapter five is on results and discussions for propagation between stairway and adjacent rooms. Results and discussions are explained in similar style as the presentation in chapter four.

Chapter six is the conclusion. This chapter discusses the inference drawn from this research study, justify the significance of the research work and give suggestions on future development based on the findings.

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