Progress In Electromagnetics Research M, Vol. 40, 69–78, 2014

Modelling the Impact of Operating Frequencies on Path Loss and Shadowing along Multi-Floor Stairwell for 0.7 GHz–2.5 GHz Range

Omar Abdul Aziz* and Tharek Abdul Rahman

Abstract—Given that building occupants and more importantly public safety personnel regularly use stairwell to move about different floors in a multi-floor building, wireless network coverage for the setting may come as necessary in order to ensure seamless telecommunication connectivity. Nevertheless, wireless network planning pertaining to multi-floor stairwell scenario requires unique radio characterization since the scenario is different from other indoor environments. This paper presents a frequency dependent path loss and shadowing model for the multi-floor stairwell environment that was developed and tested at six dog-leg style stairwells. The empirical model covers frequency spectrum from 0.7 GHz up to 2.5 GHz which envelop numerous public safety and long term evolution operating bands. The model demonstrates good precision and is shown to outperform standard path loss model when comparison was made since it includes site-specific parameters describing radio characteristics natural to stairwell setting. The straightforward mathematical expression of the model can easily be applied when setting up or studying wireless network for the stipulated frequency range with respect to multi-floor stairwell.

1. INTRODUCTION

There has been an increase in attention given to the characterization of wave propagation along multi-floor building's stairwell owing to the fact that it is among the least investigated indoor environments [1–4]. Additionally, the development of Incident Area Network (IAN) to provide communication service at emergency sites requires radio characteristics of the stairwell to be studied as public safety personnel normally use the stairwell when attending to emergency cases within a tall structure and expect uninterrupted wireless coverage [5–7]. Some analysis of propagation along stairwells using deterministic models based on ray-tracing computation have been presented in [7–9]. However, given the unique structure of the stairwell, scores of rays need to be taken into account resulting in complicated and time-consuming computation [1]. Alternatively, empirical propagation models can be employed to correctly predict anticipated path loss, PL, given a separation distance of the receiver, Rx, from a transmitter, Tx, using simpler mathematical formulation [10].

In [1], empirical PL model along the stairwell was proposed for Long Term Evolution (LTE) applications centred at 2.6 GHz with a 0.5 GHz frequency span. Another PL model for frequency bands between 2.5 GHz and 2.69 GHz with consideration of different Rx's antenna heights is presented in [2] for limited Tx-Rx distance range. Analysis of PL based on separation and walking distance along the stairwell is introduced in [3] at 2.4 GHz and 5.8 GHz. In [4], we demonstrated a PL model for the stairwell environment that took into account the effect of building's floor height as well as unique PL patterns on several stair flights, incorporating floor attenuation factors that allow easy comparison with established indoor PL models at 0.9 GHz and 1.8 GHz. While aforementioned research works investigated PL at various frequencies, the different approaches in which the formulation was developed

Received 11 November 2014, Accepted 7 December 2014, Scheduled 14 December 2014
* Corresponding author: Omar Abdul Aziz (omar@fke.utm.my).
The authors are with the Wireless Communication Centre, Universiti Teknologi Malaysia, Johor Bahru, Johor, Malaysia.

for each study did not allow easy analysis of different operating frequencies impact on expected *PL* along the stairwell.

The need to predict *PL* proficiently for a given scenario at different operating frequency bands arises because contemporary and future communication system providers use different bands that cover a wide frequency spectrum [11]. Furthermore, since small cells and carrier aggregation ability are the features to be supported by upcoming cellular system [12], radio characterization for a wide frequency range will aid in the design and deployment of these wireless networks. With respect to IAN, figuring out *PL* for various frequency bands can assist in setting up ad hoc network with similar flexibility, which is to select the best available channels to operate at, since interference in one or more channels may occur due to unprecedented events at emergency sites [13]. Hence, this paper provides essential insights of *PL* to distance relation for several frequency bands in order to facilitate wireless network planning pertaining to the stairwell setting. In the next Section 2, measurement campaign framework and procedures are explained. Section 3 describes the development of stairwell's *PL* and shadowing model. Section 4 then discusses the proposed *PL* model validation. Finally, Section 5 presents the conclusion drawn from this study.

2. MEASUREMENT FRAMEWORK AND PROCEDURES

To take advantage of 0.9 GHz and 1.8 GHz *PL* data that were acquired from previous research work for this study, we conducted further measurement campaign of *PL* in similar four stairwells that were physically described in [4]. The stairwells are referred as site 1 to site 4 as shown in Figures 1(a)–(d). The surrounding environments of the stairwells were made up of various settings and materials

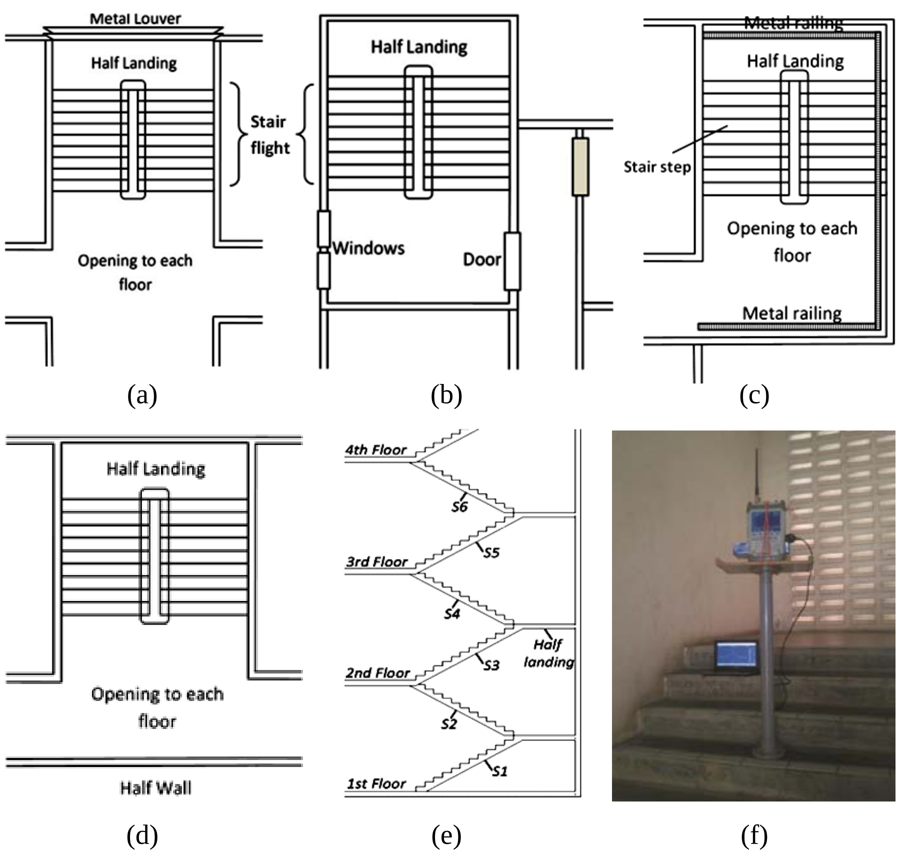


Figure 1. (a) Layout of site 1, (b) layout of site 2, (c) layout of site 3, (d) layout of site 4, (e) cross-sectional view of dog-leg stairwell investigated with stair flights labels, and (f) receiver-end setup at site 4.

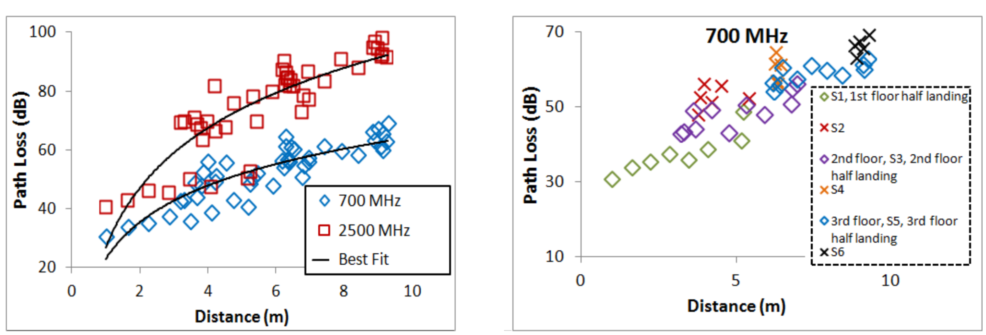
that included plastered bricks, metals, reinforced concrete beams and concrete blocks. As depicted in Figure 1(e), the stairwells were of dog-leg type with stair flights, labeled S_1 to S_6, and half landings were made of reinforced concrete while the fixed banisters or hand rails were mainly made of metal. Such a stair configuration and structure can be found in most multi-floor buildings and high rises [14, 15]. Design requirements in many countries also stipulate that components or finishing of stairwells should use materials that are not combustible for safety reason especially when the stairwells are used to exit a building on fire [16, 17]. In the measurement campaign, Tx was placed on the first floor and Rx positioned at different locations along the stairwells including the stair flights, half landings and several nearby locations on the second and third floors. It is worth mentioning that analysis in [4] demonstrated that variation in positioning of Tx along the stairwell did not introduce noteworthy changes to measured PL.

Research works are ongoing in the development of LTE technology for operation in public safety communication [18, 19]. Thus this investigation aims to support the aforementioned works by investigating LTE carrier frequencies that are close or overlaps the public safety bands [5, 19]. With recorded PL for 0.9 GHz and 1.8 GHz at hand, measurement of PL was further carried out at 0.7 GHz and 2.5 GHz. A HP/Agilent 8657B signal generator with transmitted power, $P_{tx} = 17$ Decibel-miliwatts (dBm) was used for signal transmission at 0.7 GHz while a Rohde & Schwarz SMP 22 signal generator with $P_{tx} = 21$ dBm was used to transmit 2.5 GHz signal wave. Both signal generators were supported by an elevated stand, resulting in Tx's measured height to be 1.25 meters (m) for the 0.7 GHz transmission and 1.27 m when operating at 2.5 GHz. On the other hand, a Rohde & Schwarz FSH6 handheld spectrum analyzer linked to a laptop with interface software through an optic cable made up the set up for Rx. The Rx stands 1.27 m from the ground, with the analyzer placed on top of a post. Both the Tx and Rx ends used vertically polarized Larsen SPDA24700/2700 dipole multi-band antennas that had a maximum gain of 2 dB-isotropic (dBi). To minimize the effect of small-scale fading, the Rx averaged 50 readings at each measurement point while rotating 360°.

3. STAIRWELL PATH LOSS AND SHADOWING MODEL DEVELOPMENTS

3.1. Measurement Observations

Measured PL values that were obtained were analyzed pertaining to their relation to distance in m. Figure 2(a) shows plotted PL for 0.7 GHz and 2.5 GHz at site 3. Given the maximum Tx-to-Rx separation distance in this study, maximum measured PL values at 0.7 GHz and 2.5 GHz operating frequencies are generally about 70 dB and 100 dB, respectively. As depicted in Figure 2(a), the PL differences between the two operating frequencies are more apparent with increasing Tx-to-Rx distance and separation floors. In order to ensure consistency of measured PL with that of open literature, comparison of recorded PL was made with reported results in [7]. As Rx is distantly separated from Tx for about 50 stair steps, additional PL in the range of 45 dB to 52 dB were recorded at 2.5 GHz for the measurement at all four sites. This is fairly comparable to results in [7] which reported additional PL in the range of 37 dB to 53 dB for similar Tx-to-Rx separation distance when both antennas at Rx and



(a) (b)

Figure 2. (a) Plotted PL at site 3, (b) different PL pattern plots at 0.7 GHz for site 3.

Tx-ends were vertically polarized for 2.4 GHz operation. To obtain the floor penetration factor, FPF, in dB, the same approach in [4] was employed in which recorded PL values on S_2, S_4 and S_6 were not considered. This is due to distinct PL patterns observed on these stair flights as shown in Figure 2(b), which will be dealt with afterwards.

Path loss exponents for the first floor covering measured PL on S_1, and the first half landing

Table 1. Path loss at reference distance, PL_{d0}, and path loss exponent at LOS, n_{LOS}, values.

Site	Path loss at 1 m, PL_{d0} (dB)				Path loss exponent, n_{LOS}			
	0.7 GHz	0.9 GHz	1.8 GHz	2.5 GHz	0.7 GHz	0.9 GHz	1.8 GHz	2.5 GHz
Site 1	30.71	32.63	40.26	44.06	1.78	2.32	1.34	1.53
Site 2	27.69	31.11	37.9	43.9	1.93	2.01	1.30	1.44
Site 3	30.64	30.72	38.45	40.57	1.84	2.43	1.17	1.52
Site 4	29.62	30.75	41.37	41.55	1.95	2.41	1.44	1.22

Table 2. Mean values of $FPF_{\text{1-floor}}$ and $FPF_{\text{2-floor}}$ for all investigated stairwells.

Site	1-floor penetration factor, $FPF_{\text{1-floor}}$ (dB)				2-floor penetration factor, $FPF_{\text{2-floor}}$ (dB)			
	0.7 GHz	0.9 GHz	1.8 GHz	2.5 GHz	0.7 GHz	0.9 GHz	1.8 GHz	2.5 GHz
Site 1	10.17	11.66	19	22.56	16.22	16.79	27.34	34.64
Site 2	10.98	9.95	15.96	20.99	15.08	15.52	25.47	32.94
Site 3	5.33	6.06	18.85	24.02	12.31	12.05	27.41	34.63
Site 4	6.29	5.70	16.84	23.99	11.74	10.97	24.25	32.94

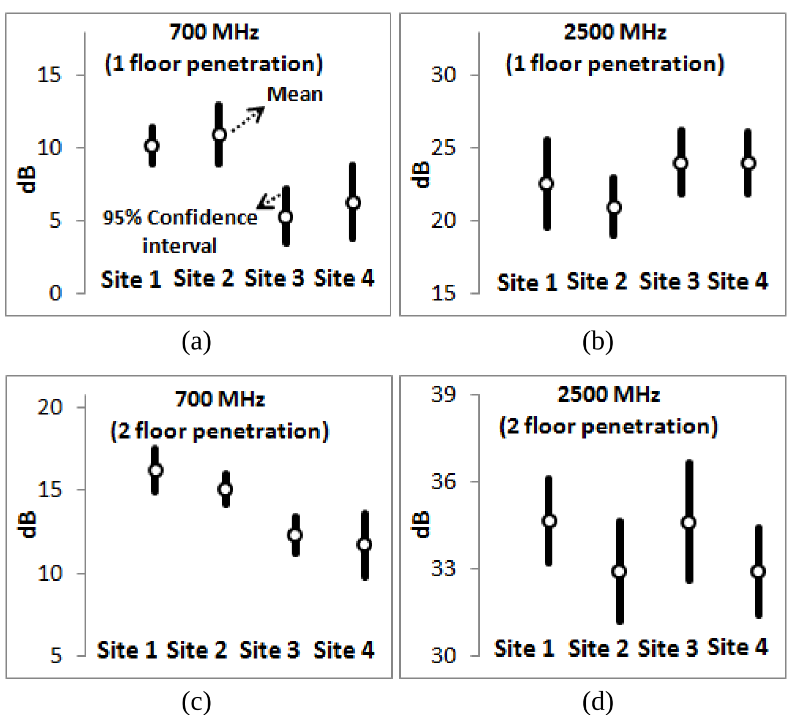


Figure 3. $FPF_{\text{1-floor}}$ with 95% confidence interval at (a) 0.7 GHz, (b) 2.5 GHz, and $FPF_{\text{2-floor}}$ with 95% confidence interval at (c) 0.7 GHz, (d) 2.5 GHz.

encountered were first acquired from regression analysis of plotted PL over distance on a log-scaled graph via least-squares technique. The covered distance is composed of S_1, and the first half landing also represents the only line-of-sight (LOS) case for the examined setting, hence the stated path loss exponents are referred as n_{LOS}. Using values of PL at reference distance or 1 m, PL_{d0}, and n_{LOS} presented in Table 1, PL was modeled using standard PL log-normal equation in (1) with d being the separation distance between Tx and Rx. Modeled PL are then subtracted from measured PL on the second and third floors to yield first floor penetration factor, $FPF_{\text{1-floor}}$, and second floor penetration factor, $FPF_{\text{2-floor}}$, respectively. Figures 3(a)–(d) demonstrate the mean and 95% confidence interval of $FPF_{\text{1-floor}}$ and $FPF_{\text{2-floor}}$ at 0.7 GHz and 2.5 GHz. Since the 95% confidence intervals in Figure 3 are not considerably large, the mean values presented in Table 2 can be considered as adequate approximation for FPF.

$$PL\left(d\right) = PL_{d0} + \left(10 \cdot n_{LOS} \cdot \text{Log}_{10}\left(\frac{d}{d_0}\right)\right) \text{ dB} \tag{1}$$

At 0.7 GHz, the 95% confidence interval of FPF for site 1 and site 2 overlaps one another in addition to having mean values that are comparable. Nevertheless, they are distinctive since the intervals do not extend to the 95% confidence interval of FPF values for site 3 and site 4 in which both overlap one another with resembling mean values. Similar characteristic has been reported for 0.9 GHz operating frequency with floor height being suggested as an influencing factor given that the floor heights for site 1 and site 2 are in the range of 3.5 m to 4.5 m whereas the floor height for both site 3 and site 4 are less than 3 m. On the other hand, the 95% confidence intervals of FPF for all four sites overlap each other at 2.5 GHz with all mean values to be found within the range of FPF's 95% confidence interval for all recorded sites. FPF for 2.5 GHz are fairly comparable to reported results for operating frequency at 1.8 GHz that shows no influence of floor height [4].

3.2. Path Loss and Shadowing Model for Stairwell Setting

To model how different operating frequencies may affect PL along the stairwell, the stairwell PL model in (2) that was proposed in [4] is used as the basis for this study. In (2), $PL(d_0)$ is the path loss experienced at reference distance, d_0, or 1 m, n_{LOS} is the PL exponent in LOS section of the stairwell, γ an added value to model the distinctive PL pattern on stair flights S_2, S_4 and S_6, d the distance in m, FPF the floor penetration factor, and $K_{correction}$ the correctional factor included to improve the PL formulation as hybrid ray consisting of reflection and wave transmitted through stair flights began to influence measured PL at S_6.

$$PL\left(d\right) = PL_{d0} + \left(10 \cdot \left(n_{LOS}\right) \cdot \left(\gamma\right) \text{Log}_{10}\left(\frac{d}{d_0}\right)\right) + FPF - K_{correction} \text{ dB} \tag{2}$$

Residuals, R, are defined as the differences between measured PL, $PL_m(d)$, and predicted PL, $PL_p(d)$, via (2). Thus, summation of R^2 or S is given in (3), where n is the total number of recorded PL for a particular setting.

$$S = \sum\nolimits_{k=1}^{n} \left|PL_m(d) - PL_p(d)\right|^2 \tag{3}$$

With the objective to minimize S, value estimation of γ and $K_{correction}$ was acquired using generalized reduced gradient (GRG) optimization algorithm. Given earlier approximation in [4], GRG starts at a feasible point = 0 and the estimated values were obtained via (4) where s and t are the total number of γ and $K_{correction}$ respectively as the equality constraints for each setting.

$$\text{Minimize } S\left(d\right) : \gamma_p = 0,\ p = 1, 2, \ldots, s \quad \text{and} \quad K_{correction\,q} = 0,\ q = 1, 2, \ldots t \tag{4}$$

To examine their relations with frequencies, parameters PL_{d0}, n_{LOS}, γ, $K_{correction}$ and FPF are plotted against f and are shown in Figure 4. Since variation of floor height may introduce effect on FPF, the FPF are plotted based on different floor height ranges. Figures 4(a)–(b) exhibit the plotted PL_{d0}, n_{LOS}, γ, and $K_{correction}$. It is observed that increasing f will result in an increase in PL_{d0}, γ, and $K_{correction}$ but a decrease in the n_{LOS} values, and the best fit for the above-mentioned relationships

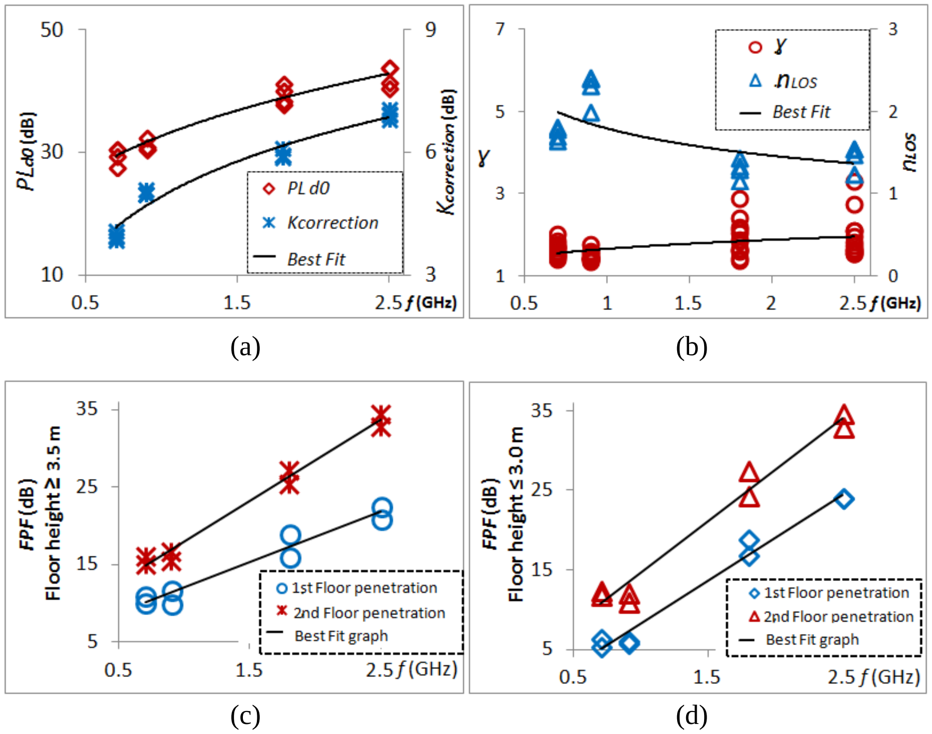


Figure 4. (a) Plots of PL_{d0} and $K_{correction}$ against f, (b) plots of γ and n_{LOS} against f, (c) plots of FPF ($3.5\,\text{m} \leq$ floor height $\leq 4.5\,\text{m}$) against f, (d) plots of FPF (floor height $\leq 3\,\text{m}$) against f.

conform to power equations as in Equations (5), (6), (7) and (8).

$$PL_{d0}\left(f\right) = 32.71\left(f^{0.3}\right)\ \text{dB} \tag{5}$$

$$n_{LOS}(f) = 1.79\left(f^{-0.3}\right) \tag{6}$$

$$\gamma(f) = 1.65\left(f^{0.18}\right) \tag{7}$$

$$K_{correction}\left(f\right) = 13.75\left(f^{0.15}\right) - 8.85\,\text{dB} \tag{8}$$

With respect to plotted $FPF_{\text{1-floor}}$ and $FPF_{\text{2-floor}}$, the best fits are correspondingly found to follow (9) and (10) linear relationship with increasing FPF values for higher f. It should be mentioned that measurement at stairwell with building's floor height between 3 m and 3.5 m is not covered in this research work and thus will benefit from supplementary study that is not within the scope of this paper.

$$FPF_{\text{1-floor}}\left(f\right) = a\cdot(f) + c\,\text{dB} \tag{9}$$

$$FPF_{\text{2-floor}}\left(f\right) = a\cdot b\cdot(f) + \ c + d\,\text{dB} \tag{10}$$

where,

$$a = \begin{cases} 6.51 & (3.5\,\text{m} \leq \text{floor height} \leq 4.5\,\text{m}) \\ 10.79 & (\text{floor height} \leq 3\,\text{m}) \end{cases}$$

$$b = \begin{cases} 1.6 & (3.5\,\text{m} \leq \text{floor height} \leq 4.5\,\text{m}) \\ 1.2 & (\text{floor height} \leq 3\,\text{m}) \end{cases}$$

$$c = \begin{cases} 5.55 & (3.5\,\text{m} \leq \text{floor height} \leq 4.5\,\text{m}) \\ -2.53 & (\text{floor height} \leq 3\,\text{m}) \end{cases}$$

$$d = \begin{cases} 2 & (3.5\,\text{m} \leq \text{floor height} \leq 4.5\,\text{m}) \\ 4 & (\text{floor height} \leq 3\,\text{m}) \end{cases}$$

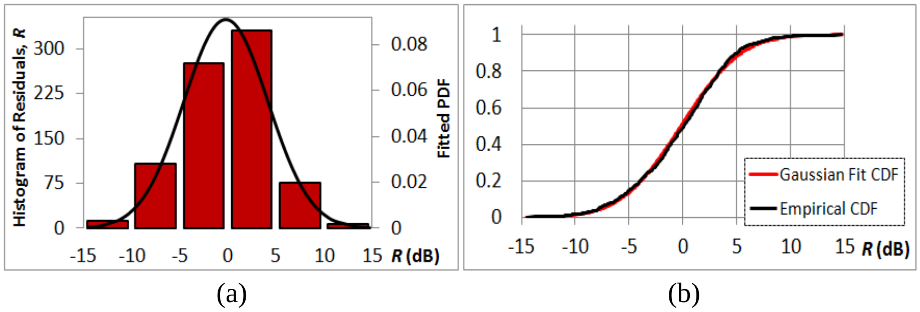


Figure 5. (a) Histogram and PDF of R, (b) CDF of R.

In order to validate precision of the parameters relation to f, shadowing, X_σ, of PL model in (2) using PL_{d0}, n_{LOS}, γ, $K_{correction}$ and FPF obtained via (5)–(10) are analyzed to describe statistically the distribution of R. Gaussian distribution is discovered to approximate the behaviour of R very well with mean $\mu_R = -0.197\,\text{dB}$ and standard deviation $\sigma_R = 4.378\,\text{dB}$. Figure 5 depicts the histogram, probability distribution function (PDF), and cumulative distribution function (CDF) of R, where $R \in (-8.5, 8.5)\,\text{dB}$ 95% of the time.

Based on the above analysis, the overall PL and X_σ expression for the multi-floor stairwell can be written as Equation (11), wherein f is in GHz

$$PL = \left(32.71 \cdot \left(f^{0.3}\right)\right) + \left(17.9 \cdot \left(f^{-0.3}\right) \cdot (\gamma) \cdot \text{Log}_{10}(d)\right) + FPF + K_{correction} + X_\sigma\,\text{dB} \tag{11}$$

where

$$\begin{aligned}
\gamma &= \begin{cases} 1.65\left(f^{0.18}\right) & \text{for stair flights } S_2,\ S_4 \text{ and } S_6 \\ 1 & \text{for all other locations} \end{cases} \\
FPF &= a \cdot b \cdot (f) + c + d\,\text{dB} \\
a &= \begin{cases} 0 & \text{first floor} \\ 6.51 & \text{higher floor } (3.5\,\text{m} \le \text{floor height} \le 4.5\,\text{m}) \\ 10.79 & \text{higher floor } (\text{floor height} \le 3\,\text{m}) \end{cases} \\
b &= \begin{cases} 0 & \text{first floor} \\ 1 & \text{second floor} \\ 1.6 & \text{third floor } (3.5\,\text{m} \le \text{floor height} \le 4.5\,\text{m}) \\ 1.2 & \text{third floor } (\text{floor height} \le 3\,\text{m}) \end{cases} \\
c &= \begin{cases} 0 & \text{first floor} \\ 5.55 & \text{higher floor } (3.5\,\text{m} \le \text{floor height} \le 4.5\,\text{m}) \\ -2.53 & \text{higher floor } (\text{floor height} \le 3\,\text{m}) \end{cases} \\
d &= \begin{cases} 0 & \text{first and second floor} \\ 2 & \text{third floor } (3.5\,\text{m} \le \text{floor height} \le 4.5\,\text{m}) \\ 4 & \text{third floor } (\text{floor height} \le 3\,\text{m}) \end{cases} \\
K_{correction} &= \begin{cases} 13.75\left(f^{0.15}\right) - 8.85\,\text{dB} & \text{for stair flight } S_6 \text{ on the third floor} \\ 0 & \text{for all other locations} \end{cases} \\
X_\sigma &\approx 4.4\,\text{dB}.
\end{aligned}$$

4. COMPARISON OF STANDARD AND PROPOSED STAIRWELL PATH LOSS MODELS

4.1. WINNER II Path Loss Model

The WINNER II path loss models for different scenarios were developed based on measurement campaign conducted for the WINNER project plus adopting numerous results from open literature.

The models can be applied to frequency range from 2 GHz to 6 GHz at various antenna heights. The model is expressed as Equation (12).

$$PL = (A \cdot \mathrm{Log}_{10} d) + B + \left(C \cdot \mathrm{Log}_{10}\left(\frac{f_c}{5}\right)\right) + X\,\mathrm{dB}, \quad FL = 17 + 4(n_f - 1)\,\mathrm{dB}\text{: } n_f > 0 \tag{12}$$

In Equation (12), A is the fitting parameter that includes path loss exponent, B the intercept, C the path loss frequency dependency, f_c the system frequency in GHz, X an optional site-specific term, and FL the floor loss with n_f being the number of floors. For indoor scenario, the WINNER II PL model is described for two cases, namely room-to-room (R-R) and corridor-to-room (C-R) settings. For LOS, A, B and C are specified as 18.7, 46.8 and 20 accordingly. For non-LOS, the values of A and B are 20 and 46.4 in R-R, whereas the values are 36.8 and 43.8 correspondingly for C-R. C is unchanged however. Since X was stated only for condition where walls were involved, the parameter was not considered when applied to the stairwell setting [20].

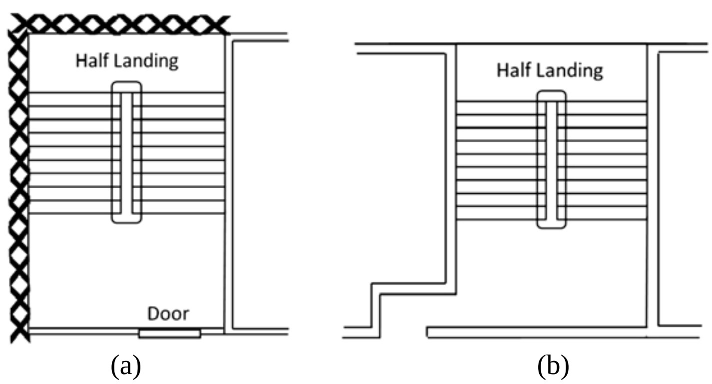


Figure 6. (a) layout of site 5 and (b) layout of site 6.

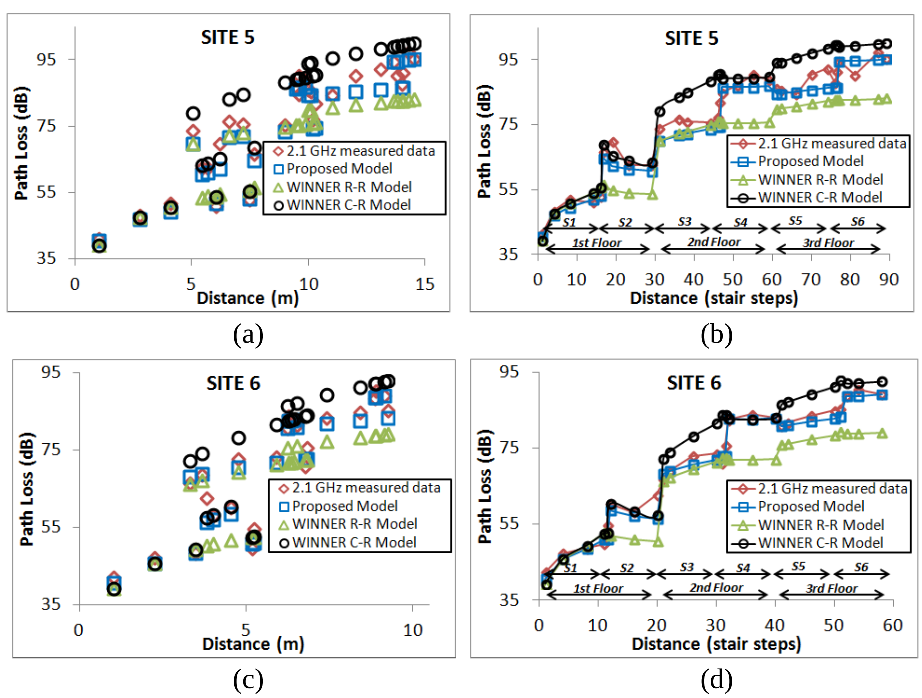


Figure 7. Measured and predicted PL at site 5, (a) x-axis distance in m, (b) x-axis distance in stair steps and site 6, (a) x-axis distance in m, (b) x-axis distance in stair steps.

Table 3. Comparison of mean errors and standard deviations between the empirical models.

Prediction Model		WINNER room-to-room		WINNER corridor-to-room		Proposed Stairwell Path Loss Model	
Site	**Frequency**	**Mean Error (dB)**	**Std. Dev. (dB)**	**Mean Error (dB)**	**Std. Dev. (dB)**	**Mean Error (dB)**	**Std. Dev. (dB)**
Site 5	**2.1 GHz**	−6.82	5.07	4.78	4.62	−2.05	2.64
Site 6		−5.41	4.48	3.03	4.22	−1.11	1.74

4.2. Comparison of Proposed and Standard Models

To inspect the proposed stairwell PL model, additional PL was recorded for another two stairwells, referred as site 5 and site 6, that have different floor heights. Site 5 resides in the same building as stairwell of site 1 while site 6 resides in a similar building to the open stairwell of site 3. Nevertheless, the layouts are dissimilar as illustrated in Figure 6. Site 5 is at the edge of the building, enclosed by plastered bricks walls and mild steel mesh grills with several vertical and horizontal reinforced concrete beams. An entrance door is present at each floor. Site 6 is located in the middle of the building with plastered brick walls enclosing the stairwell. A doorless passage allows entrance and exit from the stairwell at each floor. The stair steps widths are somewhat smaller than that of site 3. In both site 5 and site 6, PL was recorded for 2.1 GHz with the intent to investigate the reliability of the proposed model at f within the 0.7 GHz and 2.5 GHz range but exclusive of the f in which the model was developed from. Comparison was made with the WINNER II models explained earlier.

Figures 7(a)–(d) illustrate measured and predicted PL for site 5 and site 6. Measured and predicted PL values do not vary considerably for the first floor, with exception of prediction by WINNER II (R-R) model on stair flight S_2. On the second and third floors, the differences can be apparent for WINNER II models as prediction using specified R-R parameters is generally smaller whereas prediction using C-R parameters are in general larger than measured PL. The proposed stairwell PL model has the greatest prediction's accuracy, having the smallest mean error and standard deviation values as presented in Table 3. The measured standard deviations at site 5 and site 6 also do not exceed the shadowing parameter introduced in (11). The results demonstrate the soundness of the proposed model when predicting PL at various frequency bands within the 0.7 GHz and 2.5 GHz spectrum along the multi-floor stairwell.

5. CONCLUSION

This paper proposes a frequency dependent empirical path loss, PL, and shadowing, X_σ model for multi-floor stairwell environment that has been developed and validated with measured PL at six dog-leg stairwells. The layout of the stairwells examined is diverse, inclusive of open and enclosed stairwells with surroundings made from different building materials. The empirical model is intended for application at operating frequencies between 0.7 GHz and 2.5 GHz spectrum that covers numerous public safety and fourth-generation long term evolution frequency bands. The investigated settings include maximum distance that extends more than two separation floors between the transmitter, Tx and receiver, Rx, with maximum recorded PL at 0.7 GHz and 2.5 GHz being about 70 dB and 100 dB, respectively. Therefore, the proposed PL model can serve as a good reference for future research work in determining PL along the stairwell at greater separation distance between Tx and Rx especially for lower bands of the specified spectrum. As the proposed model reported sound precision and small standard deviation, the mathematical expression can thus be applied to evaluate radio characteristic of a multi-floor stairwell to aid in the design of small cell and ad hoc emergency wireless network in a straightforward manner.

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