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Investigation of Path Loss Prediction in Different Multi-Floor Stairwells at 900 MHz and 1800 MHz

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Abstract—Wireless communication along the stairwell in a high rise building is important to ensure immediate response to take place via consistent relaying of necessary information or data in emergency situations. Thus, a good understanding of signal wave attenuation along the stairwell is necessary to allow a better wireless network planning. This paper presents empirical path loss prediction model for multi-floor stairwell environment. The proposed model is based on measurement at 4 different stairwells, at 900 MHz and 1800 MHz which are near public safety communication bands. The model incorporates the effect of different floor heights and unique path loss-to-distance relation on selected stair flights observed during measurement campaign. The proposed model demonstrates higher accuracy than 3 standard path loss models at 2 other stairwells.

1. INTRODUCTION

The stairwell structure provides route for people to move about different floors in a multi-floor building. As such, wireless coverage along the stairwell, especially in emergency situations, is important to allow public safety personnel communicating and sharing information for a swift and effective response [1]. Constructed with an immense amount of concrete, the stairwell's structure minimizes radio frequency penetration from outside sources [2]. Deployment of incident area network, which is a temporary wireless network at emergency sites, may require a number of base stations, or transmission relays within the stairwell to extend wireless link especially for high-rise buildings since radiated signal is severely attenuated after just a few floors or several meters distance [3–5]. To establish an ad hoc communication system that is reliable enough to share crucial information, involving data in many forms and sizes in stairwell setting, a good awareness of how signal wave propagates in a given environment is necessary. Nevertheless, literature shows that studies of wave propagation along the stairwell are not aplenty [1].

Studies of signal attenuation along the stairwell using deterministic models [6, 7] have shown satisfactory performance but may not be apt for analytical studies since their formulation is specifically derived to run on a complex computational programme. Empirical path loss, PL models complement this shortcoming with a simpler mathematical expression that can also be easily implemented in various system-level simulators [8]. Thus in spite of advancement in many simulation techniques, empirical propagation models are widely applied in wireless modelling [9]. Many indoor empirical models have been proposed for prediction of PL in different scenarios as it is the first requirement in a system level simulator and significantly affect the computation of interference [10]. The applications of these models have been validated in various indoor environments. However, to the author's knowledge, it is difficult to find assessment of these models for multi-floor building's stairwell.

In the next section, measurement campaign framework carried out as well as analysis of observations from measured data are described. Section 3 explains the development of stairwell PL model. Section 4 presents several standard indoor propagation models plus comparison results between the standard empirical propagation models and proposed path loss model development for stairwell scenario. Finally, Section 5 discusses the inference drawn from this study.

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2. MEASUREMENT FRAMEWORK & STAIRWELL PATH LOSS MODEL DEVELOPMENT

2.1. Measurement Framework & Procedure

In this empirical study, stairwell type, most commonly built inside high rise buildings, was chosen to be investigated to ensure its significance. Literature study shows that dog-leg configuration is a generally built stairwell and has the advantage of occupying compact floor space area [11, 12]. Four dog-leg stairwells from 4 different academic and student residential building blocks inside Universiti Teknologi Malaysia's campus have been chosen for this study. The 4 stairwells are referred as Site 1 to Site 4 in this paper. Figure 1 shows Rx setup on the stair stairwell at Site 1, as well as the layout of all the stairwells.

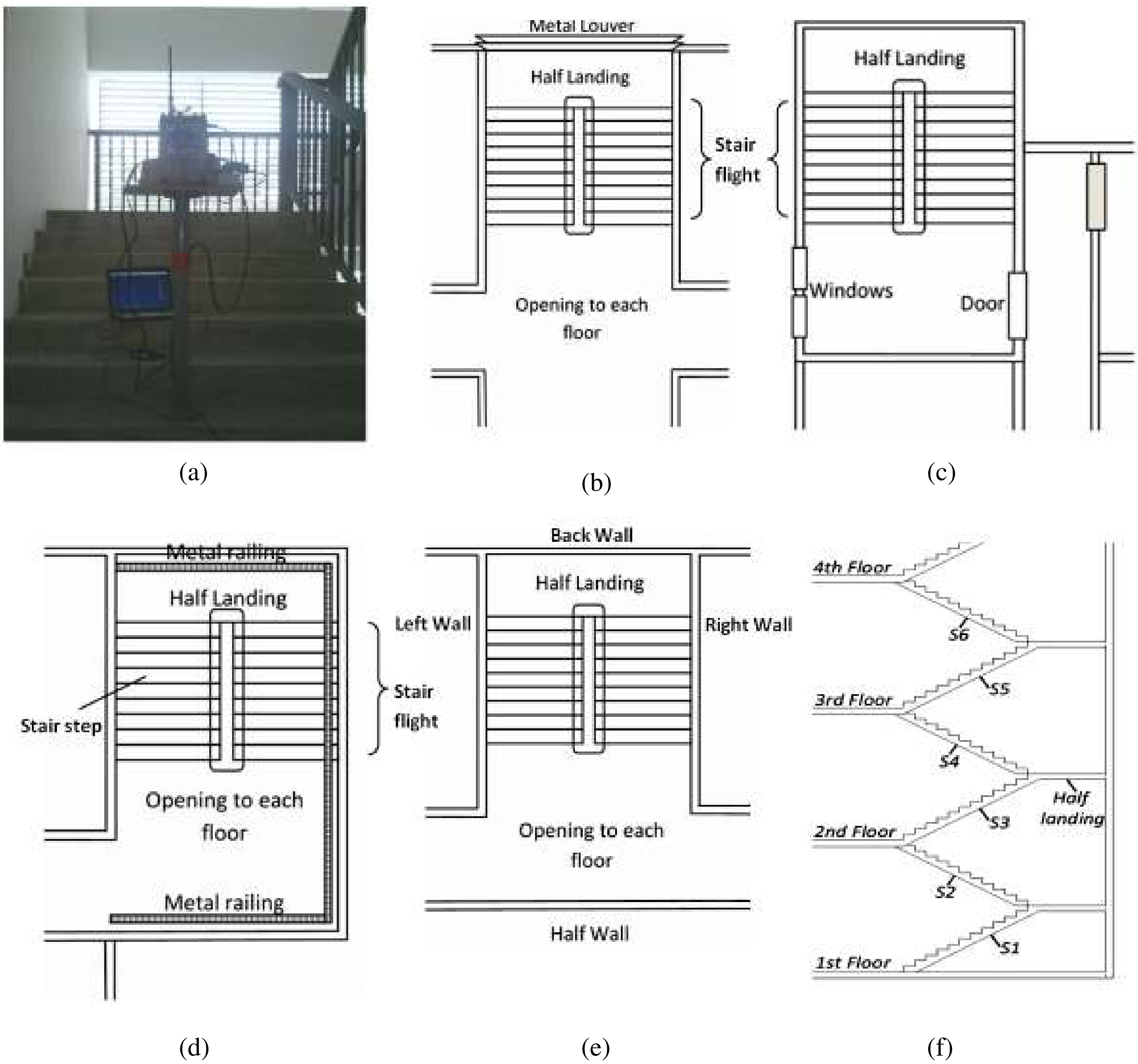


Figure 1. (a) Receiver-end setup at Site 1, (b) layout of Site 1, (c) layout of Site 2, (d) Layout of Site 3, (e) layout of Site 4 and (f) cross-sectional view of dog-leg stairwell investigated.

For reference purpose in this paper, the wall faced as one steps onto the stairwell is referred as the back wall, while the walls on the left and right are referred as left wall and right wall, respectively as in Figure 1(e). At site 1, the stairwell resides between an office and a laboratory, plus links to a large opening on each floor. The back wall is made up of a full-height aluminium alloy louver, with a 0.7 m width horizontal reinforced concrete beam about 1.75 m above each half landing. A 0.9 m height metal banister or railing is fixed at each half landing that separate the walking space from the louver. Both the left and right walls are made of plastered bricks, with a noticeable half a metre width vertical reinforced concrete beam in the middle of the stair flight at each wall. Site 2 is an enclosed stairwell with an entrance door at each floor. The enclosing walls are mainly made of plastered bricks, with selected areas of the left, back and right walls consisting of concrete blocks arrangement, which allow natural ventilation. There is also a 0.5 m width horizontal reinforced concrete beam about 1.2 m above each half landing on the back wall.

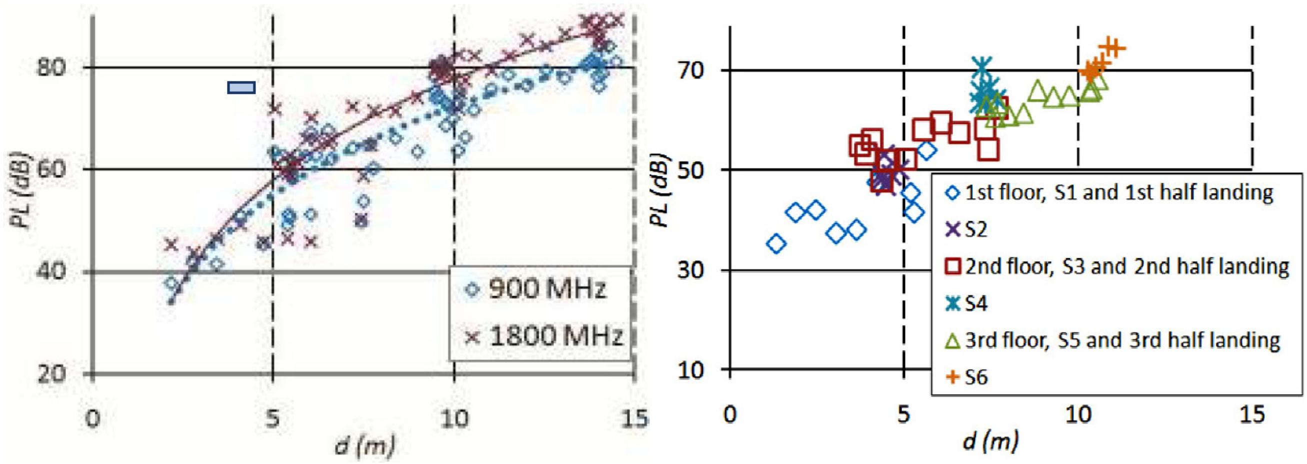
Site 3 is an open stairwell located at the side of a building. With exception of the left wall, all of the stairwell's sides are open with a 0.9 m height metal railing. At site 4, the stairwell is sandwiched between 2 residential rooms. The left, back and right walls are made of plastered bricks, and the stairwell is linked to a walking corridor with half wall at each floor. The banister at each stairwell is made of metal, though the top-panel of the hand rail for site 4 is made of wood panel. The stair steps and half landings of all the stairwells are made of reinforced concrete. It should be noted that in many countries, the law forbids the use of combustible materials in components or finishing of the stairwells used for rescue operation as well as egress from a densely populated or public building in order to allow safety exit, especially in case of building's fire [13, 14].

Tx was located at the first floor during the measurement campaign. Rx was then moved up along the stairwell from the first to reaching the fourth floor, with measurement taken at alternate stair steps including half landings at each stairwell. Radio characteristics of the stairwells were evaluated at 900 MHz and 1800 MHz which are near the public safety spectrum bands [15]. At Tx, a HP/Agilent 8657B with $P_{tx} = 17$ Decibel-miliwatts (dBm) was used for signal transmission. An elevated stand was prepared to vertically support the signal generator, bringing a total height of 1.25 meters for the Tx. The Rx included a Rohde & Schwarz FSH6 handheld spectrum analyzer which was linked to a laptop with interface software through an optic cable. The Rx stands 1.27 meters from the ground, with the analyzer placed on top of a post. Larsen SPDA24700/2700 dipole multi bands antennas with maximum gain of 2 dB-isotropic (dBi) and were used at both the Tx and Rx ends. The antennas were connected directly to the setups to avoid any cable losses. The Rx, while rotating 360° averaged 50 measured readings at each measurement point to suppress small-scale fading.

2.2. Measurement Observations

From measurement campaign carried out, PL values were obtained for signal wave transmission at all settings. It is worth noting that the highest PL from all recorded measurement at 900 MHz and 1800 MHz are 84.35 dB 90.94 dB, respectively. Figure 2(a) shows plotted PL at Site 1. Along the stairwell, the only line-of-sight (LOS) between Tx and Rx is on the first stair flight up to the centre of the first half landing. Values of PL exponent, n, were acquired from regression analysis of the plotted PL. Table 1 presents values of n for LOS condition, all measured PL at first floor that include both LOS and non-LOS condition, plus measured PL considering the effect of multi floor separation. The n_{LOS} values are shown to be consistent in addition to being smaller or near free-space condition for all stairwells. PL exponents for LOS at 1800 MHz are less than 2 while at 900 MHz the values are in the range of 2.01 to 2.43.

The short-distance segment of the stairwell where the LOS condition took place can be said to resemble an oversized waveguide structure with metal banister along the stairwell appearing as one-side of the waveguide structure's wall as in Figure 1(a). Previous studies have shown that higher wall conductivity may results in increase in signal wave attenuation in an oversized waveguide structure for signal wave propagation close to 1 GHz. However, the wall's conductivity influence on attenuation is drastically reduced at 1800 MHz [16, 17]. Thus, the non-combustible metal banisters that are commonly fitted along the stairwell to conform to fire safety requirement may have resulted in higher attenuation and consequently path loss exponent values being greater than 2 at 900 MHz for the LOS condition. Nevertheless, considering multi floor attenuation along the stairwell, signal wave at 1800 MHz has higher



(a) (b)

Figure 2. (a) Plotted PL for Site 1 and (b) different PL pattern plots at 900 MHz for Site 2.

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

Site	**Path loss at 1 m, PL_{d0} (dB)**		**Path loss exponent, n_{LOS}**		**Path loss exponent, $n_{first\ floor}$**		**Path loss exponent, $n_{multi\ floor}$**	
	900 MHz	**1800 MHz**	**900 MHz**	**1800 MHz**	**900 MHz**	**1800 MHz**	**900 MHz**	**1800 MHz**
Site 1	32.63	40.26	2.32	1.34	4.37	3.58	5.18	5.69
Site 2	31.11	37.9	2.01	1.30	2.25	2.19	4.28	4.99
Site 3	30.72	38.45	2.43	1.17	3.84	3.25	4.70	5.94
Site 4	30.75	41.37	2.41	1.44	3.85	3.04	4.17	5.36

attenuation generally compared to 900 MHz as in Figure 2(a). Figure 2(b) illustrates plots of PL for 900 MHz signal wave at Site 2. It is observed that plots of PL for stair flight $S2$, $S4$ and $S6$ are more concentrated with respect to distance in meter. Similar pattern is observed for all PL plots.

Supporting measurement campaign has also been conducted to inspect measured PL variation with different Tx locations at Site 1 and Site 2 where elevator services availability allows easy movement of the Tx setup to different floors. In the inspection carried out, Tx was placed on the third floor while Rx was positioned at different locations on the stairwell going up from the third to the fifth floor, as well as going down from the third to the first floor. 13 recorded signal strength for each directions of Rx placement on the stairwell, both moving upward and downward were obtained. Figures 3(a) and (b) show the plotted PL at 900 MHz and 1800 MHz respectively for the inspection at site 1 compared with the extensive measured PL from the first up to the third floor. The n values for the supplementary measured PL are presented in Table 2. It is noticed that the aforementioned PL plots do not demonstrate large variations from each other with all plots having nearly similar rate of PL increment with increasing distance. Similar observation was recorded at site 2.

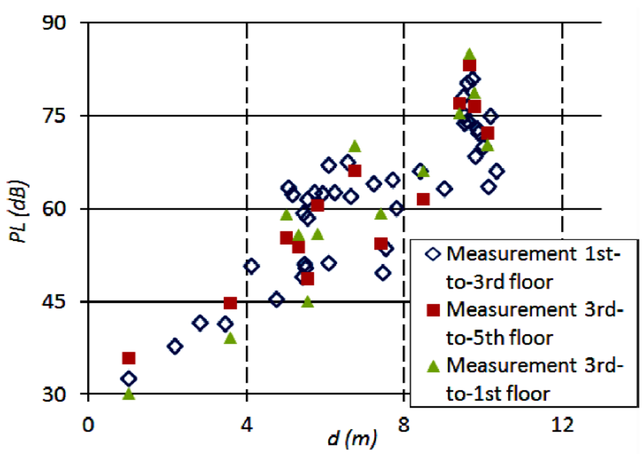
Measurement reading of the handheld spectrum analyzer during the measurement campaigns indicates that random and sparse movement up to 3 persons in a group at once along the stairwells does not cause obvious changes of the received signal strength, as their movements are usually swift.

3. STAIRWELL PATH LOSS MODEL DEVELOPMENTS

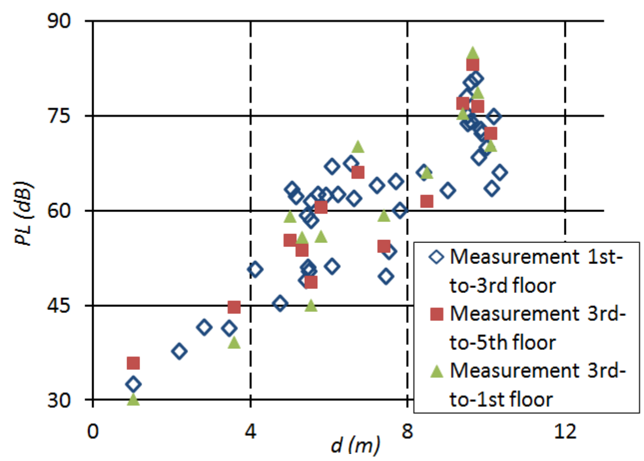
It is important to mention that the stairwell structure is different relative to other settings inside a building. The stairwell does not completely isolate the space of one floor to another plus it consists

Table 2. Path loss exponents for different Tx location along the stairwell.

Path loss exponent, n				
Measurement Scenario	Site 1		Site 2	
	900 MHz	1800 MHz	900 MHz	1800 MHz
Measured PL from 1st-to-3rd floor (Tx on 1st floor)	4.75	4.98	4.02	4.47
Measured PL from 3rd-to-1st floor (Tx on 3rd floor)	5.11	4.65	3.13	3.44
Measured PL from 3rd-to-5th floor (Tx on 3rd floor)	4.20	4.31	3.87	4.52



(a)



(b)

Figure 3. Comparison of PL plots variation from inspection and original measurement (PL from first-to-third floor) at Site 1 for (a) 900 MHz and (b) 1800 MHz.

of 2 stair flights and a half landing structure that vertically link two adjacent floors. In the following discussion, $S1$, $S3$ and $S5$ shall be referred as the lower stair flights while $S2$, $S4$ and $S6$ are referred as the upper stair flights. In many indoor empirical models, a floor attenuation or penetration factor is included to shows distinctive PL-to-distance relation at different floors [18]. In this analysis of PL at different floors along the stairwell all measured PL on the upper stair flights were first excluded due to their unique PL plots patterns as previously stated. A separate PL to-distance relation analysis on the upper stair flights shall be presented later. PL prediction for the first floor was modeled via Equation (1) that is based on standard log-normal PL model [18] and using PL_{d0} and n_{LOS} from Table 1. From Equation (1), PL values were also computed for locations with Tx-to-Rx separation distance, d, on all lower stair flights half landings and several spots that are near the stairwell on the second and third floors. The differences between computed PL using the aforementioned parameters and measured PL on the second and third floors were acquired.

$$PL = PL(d_0) + 10n_{LOS}\log_{10}\left(\frac{d}{d_0}\right) \tag{1}$$

Figure 4 shows the mean and variation at 95% confidence interval for differences between the measured and calculated PL in dB. Figure 4 also illustrate that the 95% confidence interval ranges are generally small, indicating that the mean value could provide a good estimation of floor penetration factor, FPF, for the stairwell environment. FPF at 900 MHz are observed to be influenced by floor's height for

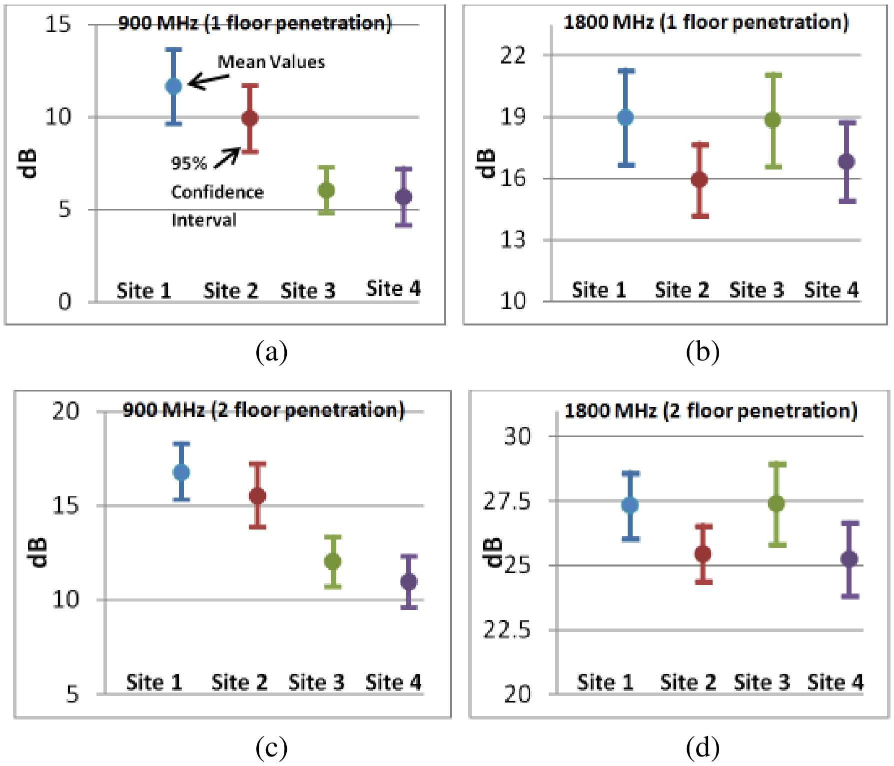


Figure 4. 1-floor penetration factor with 95% confidence interval at (a) 900 MHz, (b) 1800 MHz, and 2-floor penetration factor with 95% confidence interval at (c) 900 MHz, (d) 1800 MHz.

Table 3. Averaged 1-floor and 2-floor penetration factor (dB) for all investigated stairwells.

Site	**1-floor penetration factor, $FPF_{1\text{-}floor}$ (dB)**				**2-floor penetration factor, $FPF_{2\text{-}floor}$ (dB)**			
	900 MHz	**Avg.**	**1800 MHz**	**Avg.**	**900 MHz**	**Avg.**	**1800 MHz**	**Avg.**
Site 1	11.66	10.81 ∼ 11	19	17.66 ∼ 17.5	16.79	16.16 ∼ 16	27.34	26.12 ∼ 26
Site 2	9.95		15.96		15.52		25.47	
Site 3	6.06	5.88 ∼ 6	18.85		12.05	11.51 ∼ 11.5	27.41	
Site 4	5.70		16.84		10.97		24.25	

both 1-floor and 2-floor penetrations with site 1 and site 2 showing mean values that are close and 95% confidence interval that overlaps one another but distinctive from the means and 95% confidence interval ranges of site 3 and site 4. The floor heights of site 1 to site 4 are 4.5 m, 3.5 m, 2.9 m and 2.8 m respectively. Based on this information and using the mean value calculated, it is proposed then that the *FPF* for stairwell with floor height lesser than 3 m and for stairwell with floor height greater than 3.5 m up to 4.5 m be unique from each other at 900 MHz.

Floor height does not demonstrate apparent effect on *FPF* values at 1800 MHz as illustrated in Figures 4(b) and 4(d). Table 3 presents the approximate 1-floor ($FPF_{1\text{-}floor}$) and 2-floor penetration factor ($FPF_{2\text{-}floor}$) for *PL* prediction along the stairwell excluding the upper stair flights. The approximate *FPF* values proposed have been inspected to be within the 95% confidence interval of all the original measured *FPF* that were averaged to yield the proposed *FPF*.

Table 4. Path loss exponent, n, values for the upper stair flight ($S2$, $S4$ and $S6$).

Site	Path loss exponent, n					
	900 MHz			1800 MHz		
	S2	S4	S6	S2	S4	S6
Site 1	8.52	−10.25	7.45	2.98	16.62	6.61
Site 2	4.11	−9.56	17.14	−4.95	27.41	16.17
Site 3	1.80	26.89	23.53	6.31	−2.87	6.09
Site 4	4.11	−18.84	33.23	2.27	4.32	11.42

Table 5. Mean error (dB) and standard deviation (dB) of PL prediction on upper stair flights at 900 MHz.

Site	900 MHz								
	Stair Flight, S2			Stair Flight, S4			Stair Flight, S6		
	Values of γ ***FPF*** & $\boldsymbol{K}_{correction}$	Mean Error (dB)	Std. Dev. (dB)	Values of γ ***FPF*** & $\boldsymbol{K}_{correction}$	Mean Error (dB)	Std. Dev. (dB)	Values of γ ***FPF*** & $\boldsymbol{K}_{correction}$	Mean Error (dB)	Std. Dev. (dB)
Site 1	$\gamma = 1.6$ $FPF = 0$ $K = 0$	−0.7	4.76	$\gamma = 1.5$ $FPF = 11$ $K = 0$	0.24	3.44	$\gamma = 1.4$ $FPF = 16$ $K = 4$	−0.21	1.43
Site 2	$\gamma = 1.4$ $FPF = 0$ $K = 0$	−0.47	2.06	$\gamma = 1.5$ $FPF = 11$ $K =$	−0.43	3.37	$\gamma = 1.3$ $FPF = 16$ $K = 4$	0.45	2
Site 3	γ=1.6 $FPF = 0$ $K = 0$	0.65	4.62	γ= 1.4 $FPF = 6$ $K =$	0.72	4.79	γ= 1.5 $FPF = 11.5$ $K = 4$	−1.05	3.62
Site 4	γ= 1.6 $FPF = 0$ $K = 0$	0.02	4.83	γ= 1.3 $FPF = 6$ $K =$	−0.35	3.03	γ= 1.3 $FPF = 11.5$ $K = 4$	0.37	4.32

PL exponent or n values for the upper stair flights are shown in Table 4. Table 4 demonstrates the challenges in modelling PL to distance relation as neither frequency, nor number of penetrated floor indicates obvious effect on the PL pattern for the upper stair flights. In addition, there are also recorded PL on several of the upper stair flight that decreases in value with increasing distance. Nevertheless, approximation of PL on the upper stair flights has been attempted via mathematical expression in (2) that is based on findings in Table 3. This is to observe the relation between PL prediction on the upper stair flights and the predictions of PL on other locations along the stairwell that has been presented earlier.

$$PL_{upper\ stair\ flight} = PL(d_0) + \gamma 10 n_{LOS} \log_{10}\left(\frac{d}{d_0}\right) + FPF + K_{correction} \tag{2}$$

In Equation (2) above, γ is a multiplication factor to n_{LOS} that is intended to increase projected PL for a specific distance on the upper stair flights since n values presented in Table 4 have generally larger values compared to n_{LOS}. The FPF is 0 when computing PL on $S2$, and $FPF_{1\text{-}floor}$ and $FPF_{2\text{-}floor}$ are used to compute PL on $S4$ and $S6$ respectively. $K_{correction}$ is a correctional factor added to improve accuracy of PL prediction at different upper stair flights.

Table 5 and Table 6 present the mean errors and standard deviations of computed PL on the upper stairwells based on fine tuning of γ and $K_{correction}$ values to yield minimum mean error. Interestingly, the values of γ are found to vary slightly at each frequency setting, with the average of γ being 1.45 and 1.95 for 900 MHz and 1800 MHz respectively. The value of $K_{correction}$ is equivalent to -4 on stair flight $S6$ but can be disregarded for stair flights $S2$ and $S4$. This is due to actual PL on $S6$ being lower than predicted since signal wave reception at higher stair flights involve hybrid propagation signal wave, combining reflection and transmission through the stair flights [1].

Recalling that the n_{LOS} values in Table 1 are shown to be consistent for all investigated stairwells averaging the n_{LOS} obtained from the experiment may allow straightforward application to other stairwells. As such, the average value of n_{LOS} from the 4 investigated stairwells is approximately equal to 2.3 (900 MHz) and 1.3 (1800 MHz). Based on the analysis discussed thus far, the proposed empirical PL model for stairwell environment can be summarised in Equations (3) and (4) below.

$$
\begin{aligned}
PL_{900\,\mathrm{MHz}} &= PL(d_0) + \gamma 23 \log_{10}\left(\frac{d}{d_0}\right) + FPF + K_{correction} \\
\gamma &= \begin{cases} 1.45 & \text{for upper stair flights on second and third floor} \\ 0 & \text{for all other locations} \end{cases} \\
FPF &= \begin{cases} 0\,\mathrm{dB} & \text{for first floor} \\ 6\,\mathrm{dB} & \text{for first penetrated floor (floor height} \leq 3\,\mathrm{m)} \\ 11\,\mathrm{dB} & \text{for first penetrated floor } (3.5\,\mathrm{m} \leq \text{floor height} \leq 4.5\,\mathrm{m}) \\ 11.5\,\mathrm{dB} & \text{for second penetrated floor (floor height} \leq 3\,\mathrm{m)} \\ 16\,\mathrm{dB} & \text{for second penetrated floor } (3.5\,\mathrm{m} \leq \text{floor height} \leq 4.5\,\mathrm{m}) \end{cases} \\
K_{correction} &= \begin{cases} -4\,\mathrm{dB} & \text{for upper stair flights on the third floor} \\ 0 & \text{for all other locations} \end{cases}
\end{aligned}
\tag{3}
$$

Table 6. Mean error (dB) and standard deviation (dB) of PL prediction on upper stair flights at 1800 MHz.

Site	1800 MHz								
	Stair Flight, S2			**Stair Flight, S4**			**Stair Flight, S6**		
	Values of γ FPF & $K_{correction}$	**Mean Error (dB)**	**Std. Dev. (dB)**	**Values of γ FPF & $K_{correction}$**	**Mean Error (dB)**	**Std. Dev. (dB)**	**Values of γ FPF & $K_{correction}$**	**Mean Error (dB)**	**Std. Dev. (dB)**
Site 1	$\gamma = 2.3$ $FPF = 0$ $K = 0$	−0.47	2.18	$\gamma = 1.7$ $FPF = 17.5$ $K = 0$	0.35	0.73	$\gamma = 1.7$ $FPF = 26$ $K = 4$	0.39	1.21
Site 2	$\gamma = 2.0$ $FPF = 0$ $K = 0$	0.04	3.99	$\gamma = 1.7$ $FPF = 17.5$ $K = 0$	0.22	5.93	$\gamma = 1.6$ $FPF = 26$ $K = 4$	0.20	1.87
Site 3	$\gamma = 2.4$ $FPF = 0$ $K = 0$	0.26	2.66	$\gamma = 2.2$ $FPF = 17.5$ $K =$	−0.11	2.83	$\gamma = 2.1$ $FPF = 26$ $K = 4$	−0.18	2.20
Site 4	$\gamma = 1.7$ $FPF = 0$ $K = 0$	−0.13	3.27	$\gamma = 2.3$ $FPF = 17.5$ $K = 0$	−0.66	2.15	$\gamma = 1.7$ $FPF = 26$ $K = 4$	−0.66	0.86

$$PL_{1800\,\mathrm{MHz}} = PL(d_0) + \gamma 13 \log_{10}\left(\frac{d}{d_0}\right) + FPF + K_{correction}$$

$$\gamma = \begin{cases} 1.95 & \text{for upper stair flights on second and third floor} \\ 0 & \text{for all other locations} \end{cases}$$

$$FPF = \begin{cases} 0\,\mathrm{dB} & \text{for first floor} \\ 17.5\,\mathrm{dB} & \text{for first penetrated floor} \\ 26\,\mathrm{dB} & \text{for second penetrated floor} \end{cases}$$

$$K_{correction} = \begin{cases} -4\,\mathrm{dB} & \text{for upper stair flights on the third floor} \\ 0 & \text{for all other locations} \end{cases} \quad (4)$$

The PL models in (3) and (4) are validated with measured PL at Site 1 to Site 4. Table 7 presents the mean errors and standard deviations of the computed PL. Results in Table 7 demonstrate that the model was able to predict PL with very good precision. Stairwells with floor height between 3 m and 3.5 m were not covered in this investigation. Nevertheless, based on measured FPF as in Table 3, it is recommended that the value of FPF at 900 MHz for stairwells with such floor height to be between 6 dB and 10 dB.

Table 7. Mean error and standard deviation of PL prediction at 900 MHz at 1800 MHz.

Site	**900 MHz**		**1800 MHz**	
	Mean Error (dB)	**Std. Deviation (dB)**	**Mean Error (dB)**	**Std. Deviation (dB)**
Site 1	0.71	2.90	0.28	2.49
Site 2	−1.76	2.08	−0.08	2.79
Site 3	1.18	2.21	1.09	3.44
Site 4	−0.92	3.38	−1.88	3.59

4. COMPARISON OF STANDARD AND PROPOSED STAIRWELL PATH LOSS MODELS

Universally, 3 of the most widely used indoor empirical propagation models in many research works include the COST-231, ITUR P.1238-7, and the attenuation factor models.

4.1. COST-231 Model

The COST-231 model was first developed based on measurement carried out at 900 MHz and 1800 MHz in different buildings. In this model, the path loss, PL, in dB is

$$PL = PL_0 + 20\log_{10} d + k_f^{\left[\frac{k_f+1}{k_f+1}-b\right]} L_f + \sum_{i=1}^{k_w} k_{wi} L_{wi} \quad \mathrm{dB} \quad (5)$$

where $PL_0 = 20\log_{10}(\frac{4\pi d_0}{\lambda})$, d_0 is reference distance, that is 1 meter (m), d is distance in m, k_f is the number of penetrated floors, L_f is the loss between adjacent floors, b is a perimeter that empirically fit the effect of non linearity of path loss increment as k_f increases, while k_{wi} and L_{wi} are the number and type of walls based on categories predetermined from the studies [19].

4.2. ITUR P1238-7 Model

The ITUR P.1238-7 model is proposed based on measurement for frequency range of 900 MHz to 100 GHz. The PL in dB is calculated from the Equation (6) below.

$$PL = 20\log_{10} f + N\log_{10} d + L_f(n) - 28 \quad \mathrm{dB} \quad (6)$$

In the aforementioned model, f is frequency in MHz, N is distance power loss coefficient, with recommended values in [20], d is distance in m, L_f is the floor penetration loss factor, and n is the number of floors separating the indoor base station and mobile terminal. No wall attenuation factor is included in this model [10].

4.3. Attenuation Factor Model

The log-distance path loss model serves as the basis for this model. In addition, 2 additional terms that represent the attenuation due to walls and floors are added. Thus, PL in dB is calculated from the following equation.

$$PL = PL(d_0) + 10n \log_{10}\left(\frac{d}{d_0}\right) + FAF + \sum PAF \quad \text{dB} \tag{7}$$

In Equation (7) above, d_0 is given as 1m, n is the path loss exponent for similar floor measurement, FAF is the floor attenuation factor for a number of floors and $\sum PAF$ is the cumulative partition or wall losses along the primary ray drawn between the Tx and Rx [18].

4.4. Comparison of Standard Models

To compare the stairwell PL model that had been developed earlier with standard PL indoor models pertaining to the stairwell environment, measurement of PL have been conducted at 2 additional stairwells referred to as site 5 and site 6 in this paper. 2 stairwells have been selected for comparison purpose since both stairwells have different floor height. Stairwell of site 5 resides in similar building as the stairwell in site 1 while stairwell of site 6 resides in the same building as stairwell of site 3. However, both site 5 and site 6 have different layout in comparison to site 1 and site 3 as illustrated in Figures 5(a) and 5(b).

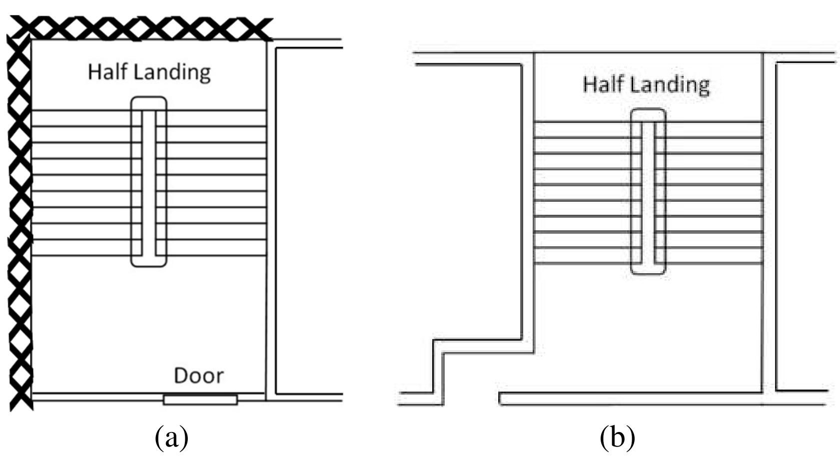


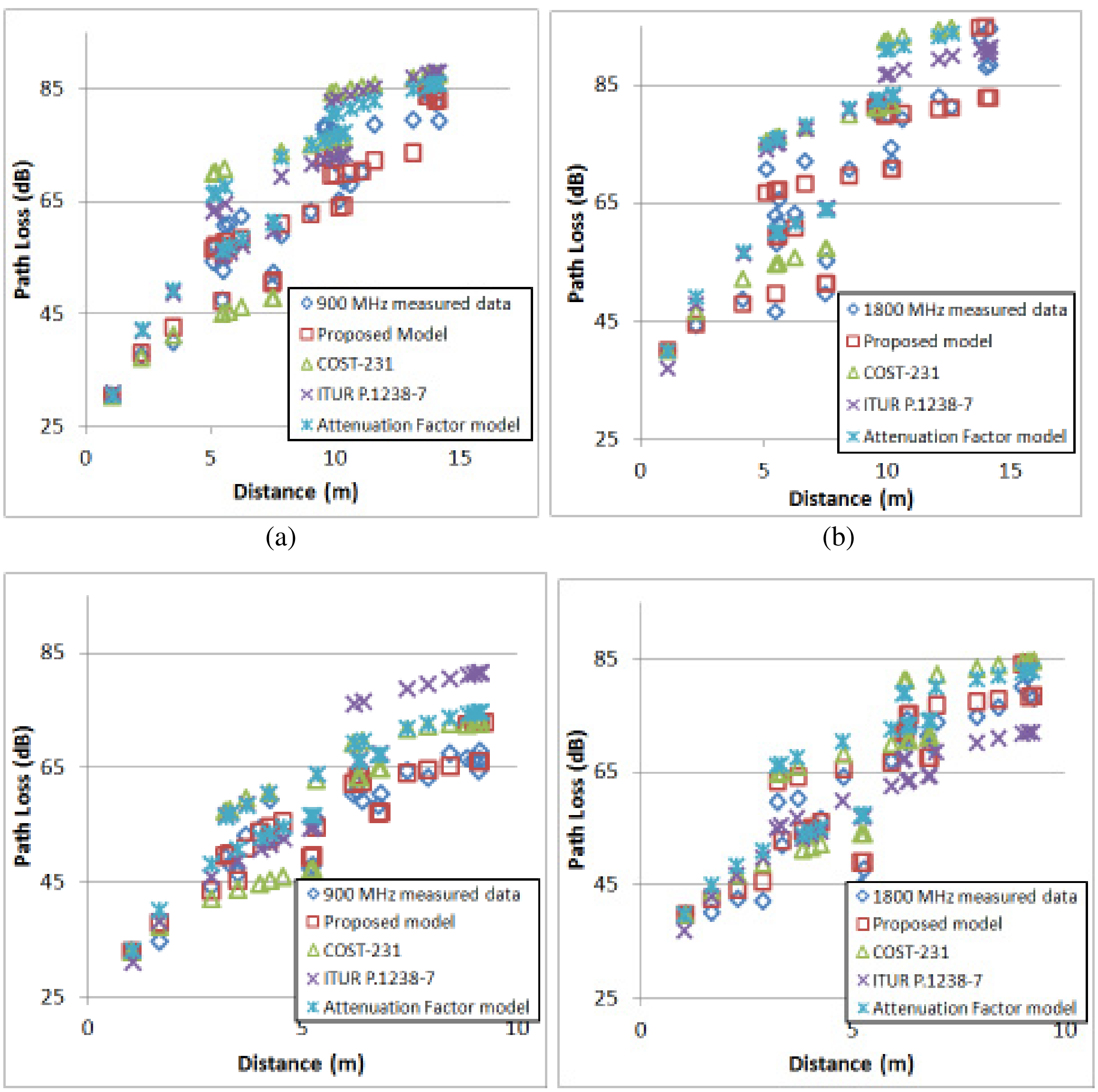
Figure 5. (a) Layout of Site 5 and (b) layout of Site 6.

The stairwell of site 5 is an enclosed stairwell with entrance door at each floor. It is located at the edge of the building, with the left and back walls made of mild steel mesh grills. There is a vertical reinforced concrete beam in the middle of the stair flight at both the left and right walls plus a horizontal reinforced concrete beam 1.75 m above each half landing. The stairwell of site 6 is located in the same building as the open stairwell of site 3. However, it is located in the middle of the building with plastered brick walls enclosing the stairwell. There is an entrance passage to the stairwell with no door as shown in Figure 5(b). The stair steps' widths are slightly smaller than that of site 3.

The measured PL_{d0} at 900 MHz and 1800 MHz are 30.55 dB and 40.1 dB for site 5, whereas the values are 33.26 dB and 39.88 dB for site 6. Table 8 presents the $n_{firstfloor}$, b and floor attenuation factor values for COST-231 and attenuation factor models. The floor attenuation factors were acquired

Table 8. Path loss exponents and floor attenuation factor.

Site	Path loss exponent, $n_{first\ floor}$		COST-231 Model		Attenuation Factor Model			
			b		Floor attenuation factor$_{1\ floor}$ (dB)		Floor attenuation factor$_{2\ floor}$ (dB)	
	900 MHz	1800 MHz	900 MHz	1800 MHz	900 MHz	1800 MHz	900 MHz	1800 MHz
Site 5	3.52	2.74	0.89	0.77	11.27	15.8	15	23.76
Site 6	3.28	2.34	0.96	0.99	6.78	13.89	10.24	19.6



(c) (d)

Figure 6. Measured and predicted path loss at (a) 900 MHz, Site 5, (b) 1800 MHz, Site 5, (c) 900 MHz, Site 6, (d) 1800 MHz, Site 6.

through finding the mean of differences between measured PL along the stairwell at second and third floors and computed PL based on model's parameters for PL prediction on the first floor. The ITUR P.1238-7 model comes with proposed values of N and L_f. The proposed N values for 900 MHz and 1800 MHz are 33 and 30 respectively in office buildings (site 5). In residential building (site 6), a slight change of N is suggested at 1800 MHz, with the value being 28. For L_f, the proposed values at 900 MHz are 9 dB and 19 dB for first and second floor penetration. At 1800 MHz, the values differ considerably between residential and office buildings. In residential building, the proposed L_f value in dB is $4n$, while in office building, $L_f = 15 + 4(n - 1)$, with n being the number of penetrated floor. Wall attenuation factor was ignored when computing PL as signal wave does not experience wall penetration.

Figure 6 presents the comparison of PL plots from measurement as well as calculation via standard empirical models and the proposed stairwell model. From the plotted graphs, it can be seen that PL calculated from the 3 standard empirical models mostly predict larger PL at second and third floors, with exception of ITUR P.1238-7 model's prediction for 1800 MHz at site 6. Table 9 shows the mean errors and standard deviations between the standard and proposed models. The proposed stairwell path loss model has the greatest precision having the smallest mean error and standard deviation values at all settings. This clearly shows the advantage in predicting PL along the stairwell when the characteristic of PL on the upper stair flights at each floor is taken into account and distinguished from expected PL on the other locations along the stairwell.

Table 9. Comparison of mean errors and standard deviations between the empirical models.

Prediction Model		**COST 231 Model**		**ITUR Model**		**Attenuation Factor Model**		**Proposed Stairwell Path Loss Model**	
Site	**Freq.**	**Mean Error (dB)**	**Std. Dev. (dB)**	**Mean Error (dB)**	**Std. Dev. (dB)**	**Mean Error (dB)**	**Std. Dev. (dB)**	**Mean Error (dB)**	**Std. Dev. (dB)**
Site 5	**900 MHz**	4.08	8.68	5.06	5.79	6.08	5.43	−1.11	2.84
	1800 MHz	5.10	5.97	4.75	5.37	6.50	5.06	−0.82	2.3
Site 6	**900 MHz**	4.26	6.20	7.71	6.82	5.88	415	0.77	2.61
	1800 MHz	4.02	4.66	3.08	5.86	4.78	4.01	1.61	1.81

5. CONCLUSION

This paper presents an empirical path loss, PL, model for multi-floor stairwell environment. The model is based on analysis of measured PL in 4 stairwells at 900 MHz and 1800 MHz, which are near public safety frequency bands. The model was validated with measured PL in additional 2 stairwells. The layout of all the stairwells investigated varied from one another. The proposed PL model takes into account the effects of different stairwells' floor height as well as distinctive PL pattern on the upper stair flights on each floor. In addition, floor penetration factors, FPF, up to 2 penetrated floors were presented. The model's prediction is very accurate, compared to 3 standard empirical propagation models. Since the mathematical expression of the model is straightforward and is developed based on measurement studies, it can directly be applied in propagation simulation tools and serve as comparison to other site-specific type models. The proposed PL model can serve as the basis for further investigation of PL prediction along building stairwells.

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