

RAIN FADE ANALYSIS AND LINK BUDGET PLANNING FOR 14.8–15.3 GHz TERRESTRIAL MICROWAVE LINKS OPERATING IN PENINSULA MALAYSIA

A.Y. Abdulrahman^{1,*} & A.T. Ajiboye²

¹Department of Electrical & Electronics Engineering, University of Ilorin, Nigeria

²Department of Computer Engineering, University of Ilorin, Nigeria

*Address all correspondence to: A.Y. Abdulrahman, Department of Electrical & Electronics Engineering, University of Ilorin, P.M.B. 1515, Nigeria; Tel.: +234-8108483222, E-mail: abdulrahmanyusuf35@gmail.com

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Most of the reported works on fade duration analyses were mainly based on the International Telecommunication Union-Radio Sector (ITU-R) method, which may not be excellently accurate for link budget analysis of terrestrial microwave links operating in tropical and equatorial climates, hence the need for this study. Others were based on experimental radio links (< 1 km path length) rather than actual operational radio links, also a motivation for this proposed study. The results of rain rate and attenuation measurements on seven geographically spread microwave links in Malaysia are analyzed in this paper. The rain attenuation data were collected from seven Digi Mini-Links operating at Ku-band (14.8–15.3 GHz) with 99.95% availability. The results were used to determine the depth of rain fade corresponding to a particular rain event on each of the links. The experimental results were also compared to the ITU-R predictions. The ITU-R rain fade predictions are comparable to those experimental values; however, a noticeable discrepancy occurs between the experimental and ITU-R path reductions. Furthermore, rain fade depth increases both with increasing path length and rain rate. Again, the receive signal levels predicted by ITU-R are higher than experimental values, especially at extremely high rain rates, due to underestimation of measured attenuation by the former. For this reason, the fade margins in link budget planning based on the ITU-R predictions come with low accuracy. The information in this study is a useful tool for link budget design and planning of terrestrial radio links operating in Peninsula Malaysia and similar tropical equatorial climates.

KEY WORDS: rain attenuation, path reduction factor, fade margin, link budget planning, exceedance probability level, terrestrial radio links

1. INTRODUCTION

The broadband fixed wireless access (BFWA) is a better promising candidate for connecting fixed users to the backbone network compared to broadband wired networks [such as digital subscriber line (DSL), hybrid fiber coax (HFC), etc.] (Ul-Islam et al., 2009; Ahmed et al., 2020; Kalaivaanan et al., 2021). BFWA has cost advantage, ease of installation, and reconfigurability among others. BFWA delivers broadband services from the base station to individual subscribers within its cell coverage area and employs a point-to-multipoint (PMP) transmission technique on

the downlink, while point-to-point (PTP) is used for the uplink. However, the performance of the microwave communication systems operating at frequencies > 10 GHz can be adversely affected by hydrometeors such as rain, cloud, fog, etc. (Freeman, 2007; Luini et al., 2020). Rain-induced attenuation is the most severe among all the afore-mentioned contributors, especially in tropical climates characterized by heavy rainfall intensities and presence of large raindrops. Thus, the transmitted signals can be absorbed, depolarized, and scattered by rain, which can cause signal attenuation, thereby reducing the reliability, availability, and performance of the communications link (Abdulrahman et al., 2014; Ajiboye et al., 2017; Abdulrahman, 2022).

Usually, propagation impairments have a significant effect only for $< 1\%$ of the time during a year ($p \leq 1\%$); therefore the system gain must be enhanced through an additional fade margin to meet the desired availability and quality of service (QoS) specifications (Paulson and Basarudin, 2011). Aside from attenuation, the performance of microwave links can also be degraded by rain fade, defined as the dynamic fluctuations of receive signal level (RSL) due to inhomogeneities of the signal path in the range of a few seconds to a few minutes. Rain fade can provide useful additional information on the link budget calculations for meeting the performance expectations, such as availability and reliability of the radio link at a particular location.

The outage probabilities of four experimental microwave links operating at 14.6, 21.95, 26, and 38 GHz were investigated in Ul-Islam et al. (2009), based on rain rate and attenuation measurements at Johor Bahru, Malaysia, near Singapore. The separation distance between the base transmit station (BTS) tower and the receivers was 300 m; hence, the path reduction was not considered in the study. Furthermore, the fade margins were calculated based on the receiver threshold and theoretical hop lengths. Therefore, the results cannot be deployed for planning the fade margins of practical terrestrial microwave links with path lengths of > 1 km.

As reported in the literature (Abdulrahman et al., 2014; Ajiboye et al., 2017; Abdulrahman, 2022), most of the works on fade duration analyses were mainly based on the International Telecommunication Union Recommendation (ITU-R) method, which either underestimates or overestimates the actual measured attenuation data. Consequently, link budget predictions derived from such a method cannot be deployed for terrestrial microwave links operating in tropical and equatorial climates, hence the motivation for this study. In this paper, the number of fade events and their corresponding durations were estimated from measurement data (rain rate and attenuation) over seven operational Digi Minilinks (14.8–15.3 GHz) in Peninsula Malaysia (see Table 1). The results were compared to those obtained from the ITU-R method and then deployed for designing the link budgets for the seven terrestrial microwave links. The empirical results of propagation measurements on the seven microwave links are contributed to the literature. The study therefore has bridged the two identified research gaps in fade duration analysis, the use of: (i) ITU-R method and (ii) nonpractical links of a < 1 km path length.

TABLE 1: Specifications of the Digi Minilinks

Type of antenna	Front-fed parabolic	
Frequency band (GHz)	14.8–15.3	
Polarization	Horizontal	
Maximum transmit power (dBm)	+18.0	
10^{-6} BER (2×2 Mbps) receive threshold (dBm)	−84.0	
Antenna beam width (deg)	2.3	
Dynamic range (dB)	50	
Antenna for both transmit and receive side	Size (m)	Gain (dBi)
	0.6	37.0

2. RAIN FADE ANALYSIS

2.1 Estimation of Receive Signal Level

According to Paulson (2010), the determination of fade experienced by a terrestrial radio link is dependent on the scattering and absorption within a volume defined by the first Fresnel zone. It has been established that 1 min rain rates are usually more extreme compared to their 1 h counterparts; this is due to the fact that smaller integration volumes yield more extremes of parameter variation. Therefore, the ITU-R P.530–14 (ITU, 2012) has proposed a set of prediction models for predicting the average annual distribution of fade, with 1 min integration time on both terrestrial and earth–space radio links (Paulson, 2010). These models are used for regulating and coordinating any radio link of interest and then for the link budget estimations. The ITU-R also provides models for fade duration and fade slope for 10 s integration time, which is mainly used in fade mitigation techniques (FMTs). The fade events and their corresponding durations derived from the measured data and ITU-R predictions were presented in this study. The RSL (measured in decibels) of any terrestrial microwave link is expressed as follows (Freeman, 2007):

$$\text{RSL} = P_t + G_t + G_r - [L_{fs} + A_g + A_R + A_w + L_r + L_t] \quad (1)$$

where P_t is the transmit power; L_t and L_r are the losses in the transmit and receive systems, respectively; G_t and G_r are the transmit and receive antenna gains, respectively; L_{fs} is the free space loss; A_g is gaseous absorption; A_R is excess attenuation due to rain on the propagation path, and A_w is the wet antenna loss on both antennas during rain; that is, A_w , transmit + A_w , receive.

The free space loss, gaseous absorptions, and excess rain attenuation are all dependent on frequency, propagation path length, and link location. The gaseous absorptions

are insignificant at frequencies of < 30 GHz. For example, the vapor absorption at 22 GHz is 0.16 dB/km. The losses in both transmit and receive systems are also negligible with respect to FSL (119.0326–136.8898 dB) at 15 GHz. The free space loss is calculated as follows (Freeman, 2007):

$$L_{fs} = 32.4 + 20\log_{10}(f_{\text{MHz}}) + 20\log_{10}(d_{\text{km}}) \quad (2)$$

where d (km) is the path length and f (MHz) is the operating frequency.

2.2 Estimation of Rain Attenuation

Rain attenuation can be directly measured over a terrestrial path or predicted from the knowledge of the link length and the horizontal distribution of the rain along the path (Mandeep, 2009; Abdulrahman et al., 2012). Rain attenuation over a terrestrial microwave path may be defined as the product of rain specific attenuation, γ_R (measured in decibels per kilometer), and the effective propagation path length, d_{eff} (measured in kilometers). The latter can be obtained from the knowledge of the link's path length, d , and the horizontally distributed rain along the path. Therefore, the attenuation A (dB) exceeded at $\%p$ of time in an average year is given in (ITU-R P.530-14, 2012):

$$A_R = \gamma_R d_{\text{eff}} \quad (3)$$

$$\gamma_R = kR^\alpha \quad (4)$$

$$d_{\text{eff}} = d.r \quad (5)$$

where R (measured in millimeters per hour) and r are the rain rate and path reduction factor, exceeded at $\%p$, respectively. Parameters k and α depend on frequency, rain temperature, and polarization; and their values can be obtained from ITU-R P.838-3 (ITU, 2005). Note that the path reduction, r accounts for the inhomogeneities of rain on the entire propagation path.

According to Recommendation ITU-R P.530-14, the rain attenuation $A_{0.01}$ (measured in decibels) at 0.01% of the time on any terrestrial microwave link is obtained by simply substituting $\%p = 0.01$ in Eqs. (3)–(5). Since the measured attenuation data, $A_{R,0.01}$ are available for each of the seven sites, therefore ITU-R method (P. 534-14) was employed to calculate the attenuation values at other exceedance probability

levels, % p . The attenuation $A_{0.01}$ at 0.01% is given by ITU-R P.838-3 (ITU, 2005), as follows:

$$A_{0.01} = k(R_{0.01})^\alpha d \left[\frac{1}{0.477(d^{0.633})R_{0.01}^{0.073\alpha} f^{0.123} - 10.579[1 - \exp(-0.024.d)]} \right] \quad (6)$$

where $R_{0.01}$ is the rain rate exceeded at 0.01%, while the term in the parenthesis represents the path reduction. The attenuation values at other exceedance probability levels, % p , can be calculated. For instance, the attenuation, A_p exceeded for $0.001\% \leq p \leq 1\%$ of the time may be deduced from the following power law:

$$\frac{A_p}{A_{0.01}} = C_1 \cdot p^{-(C_2 + C_3 \log_{10} p)} \quad (7)$$

with

$$C_1 = (0.07^{C_0})(0.12^{(1-C_0)}) \quad (8a)$$

$$C_2 = 0.855C_0 + 0.546(1 - C_0) \quad (8b)$$

$$C_3 = 0.139C_0 + 0.043(1 - C_0) \quad (8c)$$

where

$$C_0 = \begin{cases} 0.12 + 0.4 \left(\log_{10} \left(\frac{f}{10} \right)^{0.8} \right); & f \geq 10 \text{ GHz} \\ 0.12; & f < 10 \text{ GHz} \end{cases} \quad (9)$$

The predictions of the ITU-R method are valid for path lengths up to 60 km for frequencies up to 40 GHz. Empirical evidence has indicated that these models underestimate the cumulative distribution of rain attenuation when applied to microwave links located in tropical regions, thereby leading to underestimation and a poor prediction (Abdulrahman et al., 2012).

Other rain attenuation prediction methods include a revised da Silva Mello model (da Silva et al., 2007), revised Moupfouma model (Moupfouma, 2009), Lin model (1977), and synthetic storm technique (SST) (Matricciani, 1996; Pawlina-Bonati, 1999; Mandeep, 2009; Nandi et al., 2020), to mention a few. The numerical coefficients used in the da Silva Mello model were obtained by multiple nonlinear regressions, using the measured data currently available in the ITU-R databanks. SST was not considered in this study because Malaysia does not experience storms. The major drawback of both the Lin and Moupfouma models is that the two largely overestimate the measured path attenuation, more pronounced at higher rain rates. Detailed descriptions of these models can be found in the respective citations. As argued by Moupfouma (2009) and da Silva Mello et al. (2007), it is sometimes necessary to make allowance for path correction factors of > 1 . As suggested by Moupfouma, d_{eff} will be greater than the actual radio path length, if the parameter $\xi(d) < 0$, according to the following expressions:

$$d_{\text{eff}}(R_{0.01}, d) = d \cdot \exp\left(\frac{1}{\xi(d)}\right) \begin{cases} > d \text{ when } \xi(d) < 0 \\ \leq d \text{ when } \xi(d) > 0 \end{cases} \quad (10)$$

where

$$\xi(d) = \begin{cases} -100, & \text{when } d \leq 7\text{km} \\ \left(\frac{44.2}{d}\right)^{0.78}, & \text{when } d > 7\text{km} \end{cases} \quad (11)$$

3. COLLECTION OF EXPERIMENTAL DATA

Brief descriptions of measured rain rate and attenuation are presented in Sections 3.1, 3.2, and 4. Detailed descriptions can be found elsewhere; see Abdulrahman et al. (2011, 2012).

3.1 Rain Attenuation Data

The 1 s rain attenuation data were collected from seven operational terrestrial microwave links of DiGi Telecommunications Sdn. Bhd., Malaysia. Six out of the seven point-to-point microwave systems consisted of microwave Minilinks operating at 14.8 GHz, with one operating at 15.3 GHz. Each of the Minilinks was incorporated with a data acquisition and processing system. Both transmit and receive antennas were horizontally polarized (i.e., the elevation angle was ~ 0 deg) were covered with radomes during the attenuation measurements. The antennas were so carefully positioned to

ensure that the radiation pattern was such that the sidelobes were not pointing to the ground; that is, the sidelobes received an insignificant level of noise (ground contamination).

The conversion chart provided by Sony Ericsson Mobile Communications and Kista, Stockholm, Sweden (the vendors), was employed for converting the automatic gain control (AGC) levels (measured in volts) to the corresponding receive signal level in the form of equivalent power measured in decibels relative to one milliwatt (dBm). The signal is relatively stable in the clear-sky conditions as it fluctuates within ± 1 V, and the path attenuation is represented by drops in AGC levels during rain. However, the conversion process is not stable and gives fluctuations of about ± 4 dB. The maximum likely error from calibration, which may be introduced by the conversion process, is 2%, implying that the measured attenuation has accuracy of 98%. Furthermore, the dynamic range of the maximum RSL is ~ 50 dB for excess (i.e., rain) attenuation. This is adequately suitable for covering the entire dynamic range of rain attenuation for this study, except for one of the links, which has the highest total path attenuation of 53.42 dB at 0.001% of the time, “a rebuttal against the ‘49.32 dB’ erroneously reported in Abdulrahman et al. (2012).” Wet antenna attenuation has also been extracted from the actual measured attenuation so as not to contaminate the latter. Furthermore, scintillations and other atmospheric absorptions along the propagation path have not been considered in the study, as explained earlier in Section 2.1. The corresponding path attenuation, A_R is calculated by finding the difference between the RSL in clear-sky conditions, $RSL_{\text{clear sky}}$ and in a rain-filled medium, RSL_{rainy} , for horizontally polarized RSLs at the corresponding various rain rates. That is,

$$A_R = RSL_{\text{clear sky}} - RSL_{\text{rainy}} \quad (12)$$

3.2 Rainfall Rate Data

A Casella rain gauge, fitted with a programmable data logger, was positioned very close to the receiving antenna to ensure concurrent recording rain rate and attenuation data. The gauge is a tipping-bucket type, and the bucket can hold 0.5 mm of rain. Though the tipping time could not be recorded, the number of tips was recorded and stored in the built-in data logger. The availability and sensitivity of the rain gauge are 100% and 0.5 mm/min, respectively. The operating temperature range of the gauge is -10 to 50°C , and there is high reliability with a tipping accuracy of $\pm 1.00\%$. The rainfall-rate measurement duration was 12 months, with 1 min integration time. Note that all seven locations have a similar rainfall regime.

The cumulative distribution functions (CDFs) of the rain rate for the seven investigated locations are shown in Fig. 1. Those of the corresponding measured attenuation and ITU-R predictions are presented in Fig. 2, where one can see that the ITU-R predictions do not perfectly match the measured attenuations at all the exceedance probability

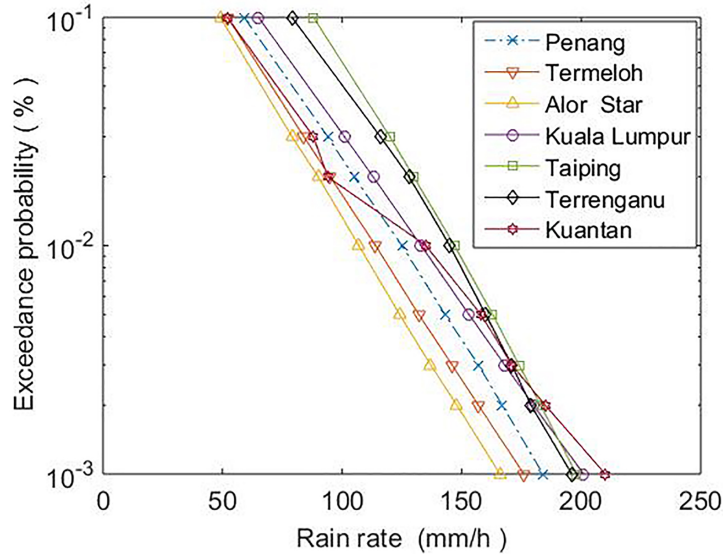


FIG. 1: Rain rate CDFs for the seven locations

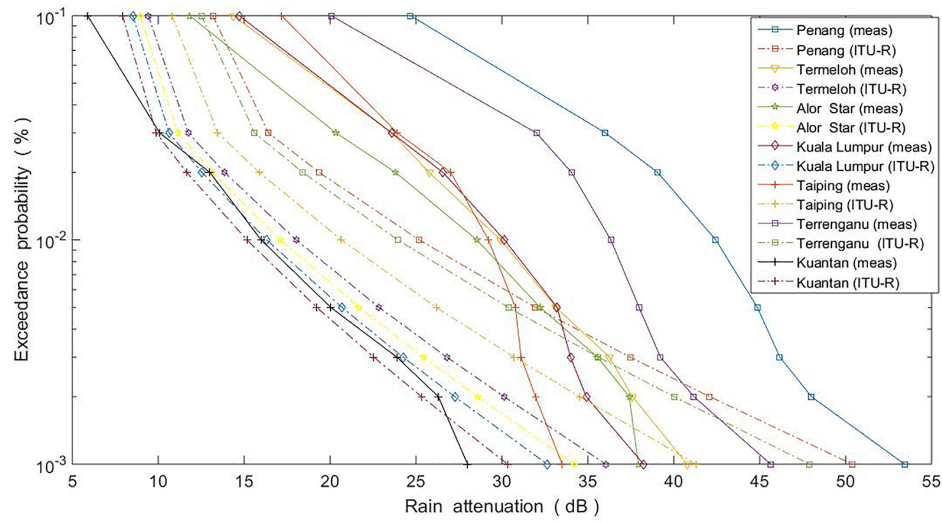


FIG. 2: Comparison of measured attenuation CDFs and corresponding ITU-R predictions

levels for three out of the seven Minilinks. However, the performance of the latest ITU-R prediction method is greatly improved compared to the older versions. For instance, the measured attenuation values for the Penang link were underestimated for $0.1 < \%p$

≤ 0.002 by the ITU-R prediction method, except at 0.001% of the time when the values roughly matched, 53.42 dB (measured) and 50.38 dB (ITU-R).

For the Taiping link, the ITU-R predictions closely match the measured attenuation values at $0.003 < \%p \leq 0.002$. For instance, the experimental values are 31.11 and 31.94 dB at 0.003 and 0.002% of the time, respectively, while the corresponding ITU-R predictions are 30.71 and 34.51 dB. For Terrenganu link, the measured attenuation values were generally underestimated for $0.1 < \%p \leq 0.03$, but there is close agreement between the ITU-R predictions and measured attenuation at extremely high rain rates for $p < 0.003\%$. For the Kuantan link, there is great agreement between the measured attenuation and ITU-R predictions for nearly all the exceedance probability levels, $0.03 < \%p \leq 0.0001$, except only at very low rain rate when $p \geq 0.1\%$. On the contrary, the measured attenuation values were generally underestimated for the links inserted at Termeloh, Alor Star, and Kuala Lumpur for the entire exceedance probability levels, $0.1 < \%p \leq 0.001$.

4. RESULTS AND DISCUSSIONS

The plots of path reduction for the seven links derived from the experimental data at the respective exceedance probability levels are shown in Fig. 3, while the experimental values of path reduction at 0.01% of the time were compared to those predicted by the ITU-R, as presented in Fig. 4. From Fig. 3, the values of path reduction derived from the experimental data from six of the Minilinks are generally less than unity, $r \leq 1.0$ (i.e., $d_{\text{eff}} < d$). However, the values of path reduction obtained from the Kuantan link do not

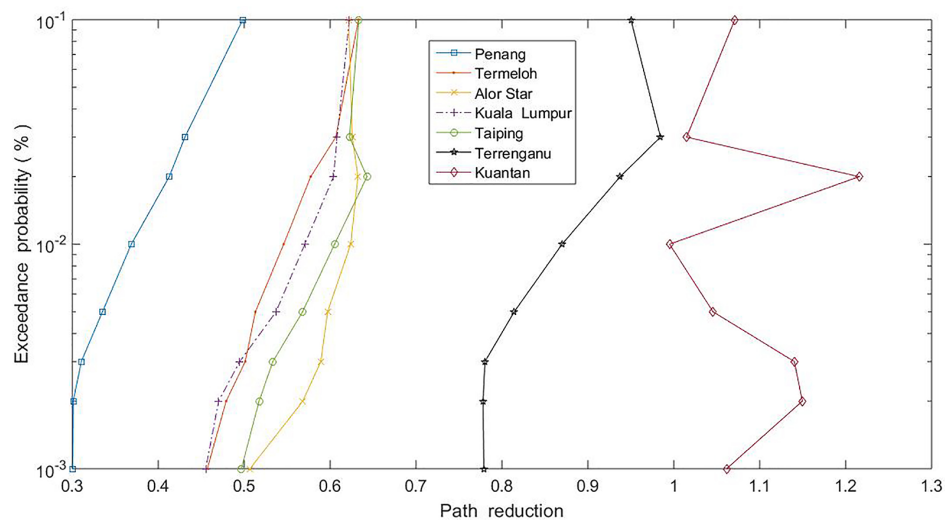


FIG. 3: Plots of path reduction at the respective exceedance probability level

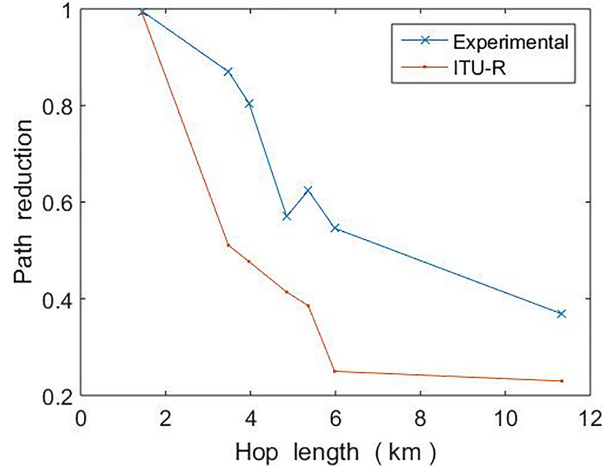


FIG. 4: Plots of path reduction against distance at 0.01% exceedance probability level

conform to the abovementioned trend, as they exhibit some interesting behavior because the values are > 1.0 for all $\%p$ of the time, except for 0.001% when the value is 0.995. This is justifiable according to da Silva Mello et al. (2007) and Moupfouma (2009) [see Eqs. (10) and (11)]. Moreover, from Fig. 4, the experimental values of path reduction at 0.01% and those predicted by the ITU-R are both generally < 1.0 , $r < 1.0$. The former is in the range 0.369–0.995, while the latter has a range of 0.23–0.99. Generally, the former has higher path reduction values for all seven links; however, the values are roughly the same at the Kuantan link, 0.995 and 0.99, respectively. This is because, as mentioned earlier, the measured attenuation was underestimated by the ITU-R model for all seven links.

It can be inferred from Eq. (6), that the effective path length at 0.01% of the time, $d_{\text{eff},0.01}(R_{0.01}, d, f)$ depends on rain rate at 0.01% of the time, $R_{0.01}$; path length, d ; and operating frequency, f . Furthermore, path reduction is the only variable that is usually manipulated in most of attenuation prediction models [see Eqs. (3) and (5)]. Hence, it is the major yardstick for comparing rain attenuation models (Abdulrahman et al., 2011), since γ_R and d are usually not manipulated. The free space loss, L_{fs} , was plotted against the respective path length for each of the links in Fig. 5, using the respective links' path lengths and operating frequencies as inputs in Eq. (2). Also, the RSLs derived experimentally and those from the ITU-R predictions are plotted in Fig. 6.

As expected, L_{fs} increased with increasing length at a given frequency of operation as shown in Fig. 5. Theoretically, for a given operating frequency, f , the RSL of a transmitted radio signal decays as the square of the path length, d , between the transmitter and receiver, ($\text{RSL} \propto d^{-2}$) increases, according to inverse square law (Freeman, 2007). However, in reality, radio path length may not be the only predominantly contributing

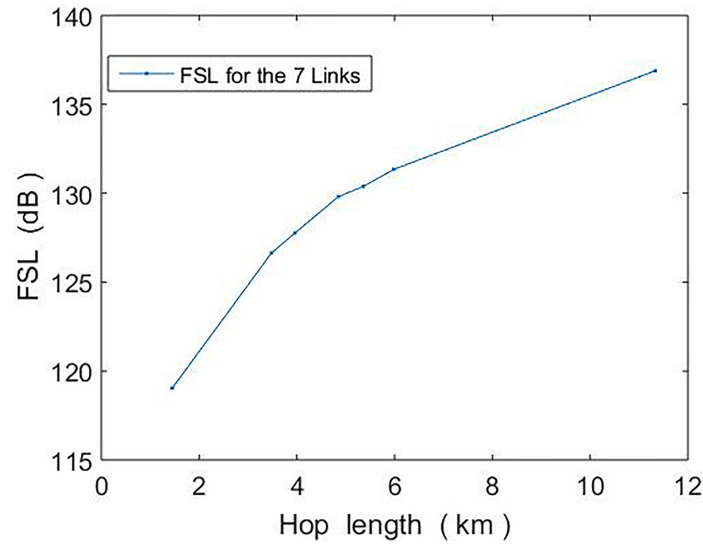


FIG. 5: Plots of FSL against distance for the seven links

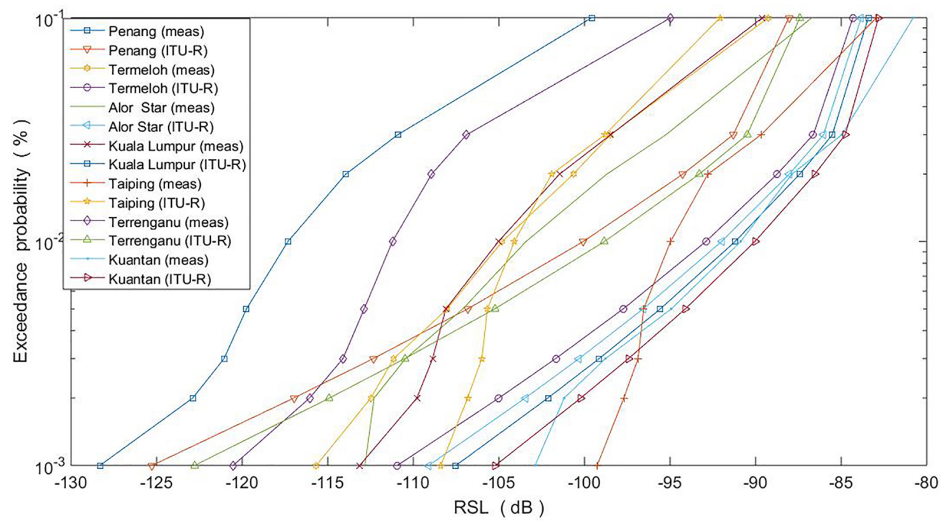


FIG. 6: RSL for the seven CMLs at 0.01% the corresponding exceedance probability level

factor, depending on the propagation scenario (s). For instance, a signal transmitted in clear-air conditions over a longer path length may experience a lesser fade (a higher RSL) compared to when it is otherwise transmitted in a rain-filled medium over a shorter path length (a higher RSL). Therefore, serious attention is usually given to the

prevailing propagation conditions in the estimation of fade over a terrestrial microwave link.

The results of RSLs presented in Fig. 6 are highlighted in Table 2 (where, as noted, the total number of fade events is 14). Eight fade events were observed at the Penang link; six were obtained experimentally and two from the ITU-R predictions.

The six fade events occurred when rain rate had a range of $105 \leq R \leq 184$ mm/h corresponding to $0.02 \leq p \leq 0.001\%$, while the two ITU-R predicted fade events occur only when the rain rate is extremely high, $167 \leq R \leq 184$ mm/h, which corresponds to $0.002 \leq p \leq 0.001\%$. Note that a critical value of RSL ($-113.95 \approx -114$ dB) is observed from the experimental data at 0.002% of the time. Furthermore, five fade events were recorded at the Terengganu link, three obtained from experimental data and two from the ITU-R predictions. The three fades occur when $0.003 \leq \%p \leq 0.001\%$, which corresponds to $171 \leq R \leq 196$ mm/h, while the two fades from the ITU-R predictions occur when $0.002 \leq p \leq 0.001\%$, which corresponds to $179 \leq R \leq 196$ mm/h. Lastly, only a fade event (experimental) was observed at the Termeloh link, when $p \leq 0.001\%$, corresponding to $R \geq 196$ mm/h. No fade event was recorded for the Digi Minilinks inserted at Alor Star, Kuala Lumpur, Kuantan, and Taiping. Therefore, based on these results as presented in Table 2 and Figs. (7)–(9), one can conclude that the ITU-R method may not be suitable for planning the link budget of the four links that were not faded by rain.

The number of fade events for each of the Minilinks is shown in Fig. 7, while the plots of faded RSLs against duration in an average year are presented in Fig. 8. As noted in Fig. 7, there are seven actual links and seven ITU-R hypothetical links, out of which fade events were only observed at the Penang link (plus the ITU-R predictions), Terengganu link (plus the ITU-R predictions), and Termeloh link. Note that the plot for the Termeloh is not highlighted in Fig. 8 because it has only one data point, i.e., only a fade event was observed. The results of fade duration against RSL (presented in Fig. 8) are interpreted in Fig. 9 with the aid of bar charts.

As can be seen from Fig. 9, only one link experiences the longest fade durations 105.12 min, at a low rain rates $R \leq 59$ mm/h, with the lowest fade depths, while the shortest outage duration, 5.256 min, is observed for five links (three actual and two ITU-R) at high-extreme rain rates in the range $176 \leq R \leq 196$ mm/h, characterized by the deepest fade depths. These results further corroborate the claim in Paulson (2010) that propagation impairments usually have a significant effect only for $< 1\%$ of the time during a year ($p \leq 1\%$).

5. CONCLUSIONS

The measured rain rate and attenuation over seven geographically spread operational terrestrial microwave links in Peninsula Malaysia were analyzed in this study. The measured attenuation was compared to predictions of the ITU-R method for each of the seven links. Furthermore, the path reduction and receive signal levels, both derived from the experimental results, were also compared to those of the ITU-R predictions. When compared to the measurement data, the predictions of the ITU-R method are relatively

TABLE 2: Fade margins due to rain at the respective p (%) of the year for the seven links

	Digi Minilinks	RSL (dB)							$Rx_{th} = -114$ dB fade events recorded
		Exceedance probability, % p							
		0.1	0.02	0.01	0.005	0.003	0.002	0.001	
Penang 11.33 km; 14.8 GHz	Exp	-99.57	-113.95	-117.33	-119.75	-121.06	-122.89	-128.31	$0.02 \leq \%p \leq 0.001$
	ITU-R	-88.06	-94.26	-100.07	-106.83	-112.34	-116.98	-125.27	$0.002 \leq \%p \leq 0.001$
Termeloh 5.98 km; 14.8 GHz	Exp	-89.25	-100.66	-104.80	-108.03	-111.14	-112.48	-115.67	$p \leq 0.001\%$
	ITU-R	-84.31	-88.74	-92.91	-97.74	-101.68	-105.00	-110.93	None
Alor Star 5.36 km; 14.8 GHz	Exp	-86.71	-98.70	-103.42	-107.11	-110.45	-112.29	-112.83	None
	ITU-R	-83.83	-88.07	-91.99	-96.57	-100.32	-103.46	-109.09	None
Kukala Lumpur 4.85 km; 15.3 GHz	Exp	-89.60	-101.46	-105.03	-108.10	-108.87	-109.79	-113.13	None
	ITU-R	-83.42	-87.43	-91.19	-95.57	-99.14	-102.14	-107.51	None
Taiping 3.96 km; 14.8 GHz	Exp	-92.07	-101.92	-104.10	-105.67	-106.00	-106.83	-108.39	None
	ITU-R	-82.94	-92.79	-94.97	-96.54	-96.87	-97.70	-99.26	None
Terrenganu 3.48 km; 14.8 GHz	Exp	-94.95	-108.93	-111.22	-112.87	-114.11	-116.06	-120.53	$0.003 \leq \%p \leq 0.001$
	ITU-R	-87.41	-93.30	-98.83	-105.25	-110.49	-114.90	-122.78	$0.002 \leq \%p \leq 0.001$
Kuantan 1.45 km; 14.8 GHz	Exp	-80.78	-87.89	-90.87	-94.93	-98.77	-101.19	-102.89	None
	ITU-R	-82.82	-86.54	-90.04	-94.11	-97.43	-100.22	-105.21	None

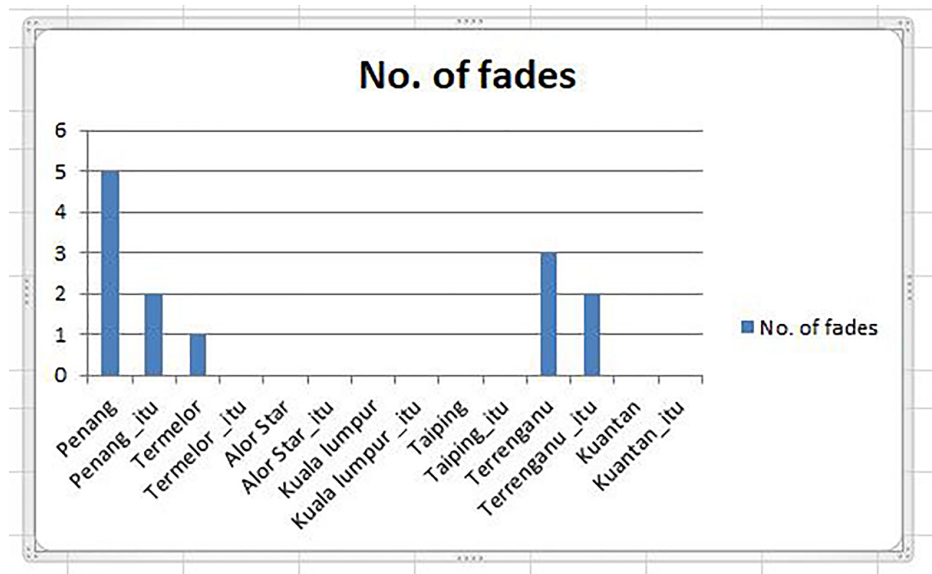


FIG. 7: Number of fade events

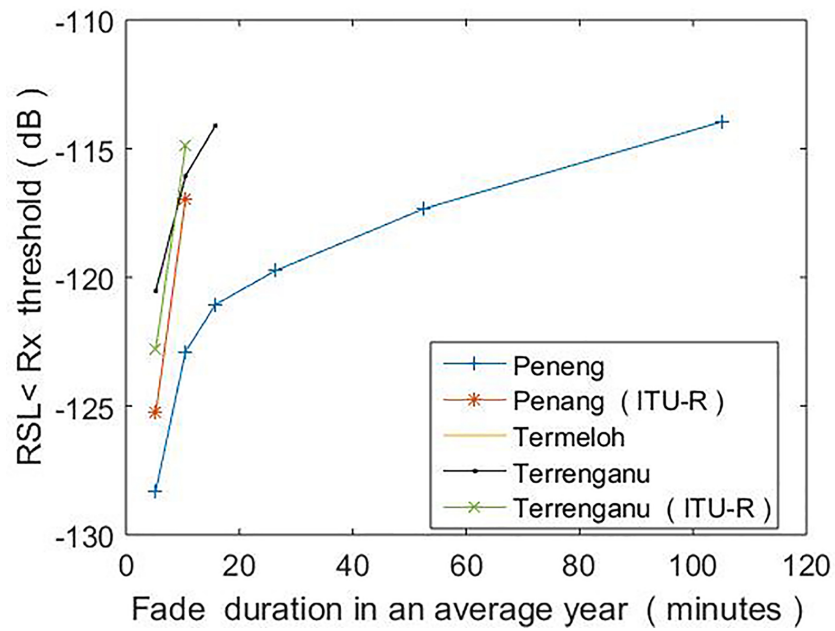


FIG. 8: Faded RSLs against duration in an average year

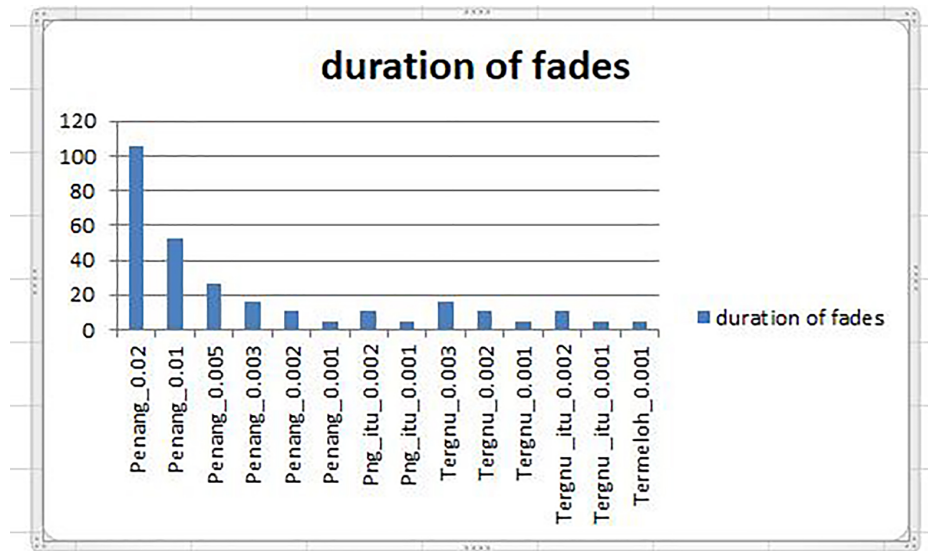


FIG. 9: Faded links and the corresponding to fade duration

accurate for the majority of the links over a wide range of the exceedance probability level. This shows a great improvement in the ITU-R method compared to its older versions. The values of path reductions, both experimental and ITU-R predictions, are generally < 1.0 for six links, with only the Kuantan link not conforming with the usual trend. The values of path reduction at the Kuantan link are > 1.0 , except at 0.001% of the time when it is 0.995. This unusual behavior to make allowance for path reductions of > 1.0 has been proven by both Moupfouma (2009) and da Silver Mello et al. (2007). That is, the effective path length can sometimes be greater than the actual radio path length, depending on the prevailing propagation conditions. Furthermore, both the experimental values of path reduction at 0.01% of the time and those predicted by the ITU-R are all < 1.0 . The RSLs from the ITU-R predictions are generally higher than those obtained experimentally; hence, the rain fades predicted by the former are less.

The number of rain fade events and their corresponding durations were estimated from the measurement data, compared to those obtained from the ITU-R method and then deployed for designing the link budgets for the seven terrestrial microwave links. A total 14 fade events were observed: ten experimental and four from the ITU-R predictions. The ten fade events observed experimentally were from three out of the seven links, while the four fade events from the ITU-R method predicted were from only two links. No fade event was recorded at Alor Star, Kuala Lumpur, Kuantan, and Taiping over the range of $0.001 < p < 0.1\%$. A few of the ITU-R results are comparable to the experimental values.

Most of the reported works on fade duration analyses were based on the ITU-R method, and a few of such studies were based on experimental radio links rather than actual opera-

tional radio links. As revealed in this study, the ITU-R method is not perfectly adequate for planning the link budgets of terrestrial radio links in the studied climates. The empirical results of propagation measurements on the seven microwave links are contributed to the literature. The study therefore has bridged the two identified research gaps in fade duration analysis, the use of: (i) the ITU-R method and (ii) nonpractical links of < 1 km path length. The information provided in this study can serve a useful tool for link budget design and planning of terrestrial radio links in similar tropical and equatorial climates.

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REFERENCES

- Abdulrahman, A.Y., Rahman, T.A., Rahim, S.K.A., and Islam, M.R., Empirically Derived Path Reduction Factor for Terrestrial Microwave Links Operating at 15 GHz in Peninsula Malaysia, *J. Electromagn. Waves Appl.*, vol. **25**, pp. 23–37, 2011.
- Abdulrahman, A.Y., Rahman, T.A., Abdulrahim, S.K., and Islam, M.R., Rain Attenuation Measurements over Terrestrial Microwave Links Operating at 15 GHz in Malaysia, *Int. J. Commun. Syst.*, vol. **25**, no. 11, pp. 1479–1488, 2012.
- Abdulrahman, A.Y., Rahman, T.A., Islam, M.R., Olufeagba, B.J., Abdulrahman, T.A., Akanni, J., and Amuda, S.A.Y., Investigation of the Unified Rain Attenuation Prediction Method with Data from Tropical Climates, *Antennas Wirel. Propag. Letts.*, vol. **13**, pp. 1108–1111, 2014.
- Abdulrahman, A.Y., Analysis of Wet Antenna Losses on 11.843 GHz Slant Path in Nigeria and Comparison with Some Tropical Climates, *J. Microw. Optoelectron. Electromagn. Appl.*, vol. **21**, no. 2, pp. 207–219, 2022.
- Ahmed, M.A., Michael, C., Marshad, M., Marwan, H.A., and Yun, A., Statistical Analysis of Rain at Millimeter Waves in Tropical Area, *IEEE Access*, vol. **8**, pp. 51044–51061, 2020.
- Ajiboye, A., Abdulrahman, A.Y., Falade, A.J., Ajiboye, A.T., Zakariyya, O.S., and Rahman, T.A., Effects of Ionospheric Scintillation on Communication Systems: GPS and Satellite, *J. Telecommun. Radio Eng.*, vol. **76**, no. 20, pp. 1849–1859, 2017.
- da Silva Mello, L.A.R., Pontes, M.S., De Souza, R.M., and Perez Garcia, N.A., Prediction of Rain Attenuation in Terrestrial Links Using Full Rainfall Rate Distribution, *Electron. Lett.*, vol. **43**, no. 25, pp. 1442–1443, 2007.
- Freeman, R.L., Ed., *Radio System Design for Telecommunication*, 3rd Ed., Hoboken, NJ: Wiley, 2007.
- Kalaivaanan, P.M., Sali, A., Raja, S.A.R.A., Syamsuri, Y., Mandeep, J.S., and Ali, M.A., On the-Move Measurement Analysis for Ka-Band High Throughput Satellite and LiFi Communication Networks in Tropical Region, *IEEE Access*, vol. **9**, pp. 71344–71355, 2021.
- Lin, S.H., National Long-Term Rain Statistics and Empirical Calculation of 11 GHz Microwave Rain Attenuation, *Bell Syst. Tech. J.*, vol. **56**, no. 9, pp. 1581–1604, 1977.
- Luini, L., Roveda, G., Zaffaroni, M., Costa, M., and Riva, C.G., The Impact of Rain on Short E-Band Radio Links for 5G Mobile Systems: Experimental Results and Prediction Models, *IEEE Trans. Antennas Propag.*, vol. **68**, no. 4, pp. 3124–3134, 2020.

- Mandeep, J.S., Rain Attenuation Statistics over a Terrestrial Link at 32.6 GHz at Malaysia, *IET Microw. Antennas Propag.*, vol. **3**, no. 7, pp. 1086–1093, 2009.
- Matricciani, E., Physical-Mathematical Model of the Dynamics of Rain Attenuation Based on Rate Time Series and a Two-Layer Vertical Structure of Precipitation, *Radio Sci.*, vol. **31**, no. 2, pp. 281–295, 1996.
- Moupfouma, F., Electromagnetic Waves Attenuation Due to Rain: A Prediction Model for Terrestrial or L.O.S SHF and EHF Radio Communication, *J. Infrared Millim. Terahertz Waves*, vol. **30**, pp. 622–632, 2009.
- Nandi, D., Pérez-Fontán, F., Pastoriza-Santos, V., and Machado, F., Application of Synthetic Storm Technique for Rain Attenuation Prediction at Ka and Q Band for a Temperate Location, Vigo, Spain, *Adv. Space Res.*, vol. **66**, no. 4, pp. 800–809, 2020.
- Paulson, K.S., Trends in the Incidence of Rain Rates Associated with Outages on Fixed Links Operating above 10 GHz in the Southern United Kingdom, *Radio Sci.*, vol. **45**, pp. 1–9, 2010.
- Paulson, K.S. and Basarudin, H., Development of a Heterogenous Microwave Network Fade Simulation Tool Applicable to Networks that Span Europe, *Radio Sci.*, vol. **46**, pp. 1–6, 2011.
- Pawlina-Bonati, A., Essential Knowledge of Rain Structure for Radio Applications Based on Available Data and Models. *Proc. of Third Regular Workshop on Radio Communications in Africa*, Gaborone, Botswana: Radio Africa, pp. 1–11, 1999.
- ITU, Specific Attenuation Model for Rain for Use in Prediction Methods, *Int. Telecommunication Union*, Geneva, Switzerland, Recommendation ITU-R P.838–3, 2005.
- ITU, Propagation Data and Prediction Methods Required for the Design of Terrestrial Line-of-Sight Systems, *Int. Telecommunication Union*, Geneva, Switzerland, Recommendation ITU-R P.530–14, 2012.
- Ul-Islam, M.R., Rahman, T.A., Rahim, S.K.A., Al-tabatabaie, K.F., and Abdulrahman, A.Y., Fade Margins Prediction for Broadband Fixed Wireless Access (BFWA) from Measurements in Tropics, *Prog. Electromagn. Res. C*, vol. **11**, pp. 199–212, 2009.

