Indonesian Journal of Electrical Engineering and Informatics (IJEEI)
Vol. 7, No. 3, Sep 2019, pp. 472~483
ISSN: 2089-3272, DOI: 10.11591/ijeei.v7i3.956

Rain Attenuation at Tropical Region - Site Diversity Gain Models's sensitivity

Fazdliana Samat, Mandeep Singh Jit Singh
Centre of Advanced Electronic and Communication Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia

Article Info

Article historys:

Received Jan 07, 2019
Revised May 01, 2019
Accepted Sep 06, 2019

Keywords:

Diversity Gain
Rain Fade Mitigation
Signal Degradation
Atmosphere effect
Gain Factors

ABSTRACT

Site diversity is one of the effective techniques to avoid rain attenuation especially in tropical region. Therefore, the performance of site diversity scheme is measured using site diversity gain. However, due to lack of measurement data availability, an empirical model to calculate the gain was initiated by Hodge. From this initiative, the model was improvised to suit various data, locally. In this paper, the factor that impacted the total gain that are the frequency, baseline angle, separation distance and elevation angle are discussed. Even though several models were proposed to extend the capability of Hodge's model, there are still uncertainty in their performance. Therefore, in this paper, model of Hodge, Panagopolous, ITU-R, Semire and X. Yeo were investigated to observe their reactivity towards the four factors. Each model was set default at 20.2GHz, 68.8° of elevation angle, 65° of baseline angle and 42.52km of site separation distance. However, the configuration is not fixed, since each contributor's value is altered to form 16 combinative test lists. Each models percentage of change were recorded and the value of predicted gain by each model was presented. The models sensitiveness towards the contributors were also presented in a table to ease for future references.

Copyright © 2019 Institute of Advanced Engineering and Science.
All rights reserved.

Corresponding Author:

Fazdliana Samat,
Center of Advanced Electronics and Communication Engineering,
Faculty of Engineering and Built Environment,
Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia.
Email: fazdliana@yahoo.com.my

1. INTRODUCTION

Satellite communication becomes demanding services nowadays due to advancing technology of wireless communication and broadband internet application. The used of Ka-Band and above frequency is one of the solutions to cater these needs. However, at this high frequency of above 20 GHz, Ka-Band signal that propagates through the earth atmosphere are susceptible to propagation impairment especially rain, at double effect than the lower frequency; Ku-band [1]. The rain adds to the severity of signal attenuation, which is already experiencing a lack of energy and amplitude when propagating towards the earth from the Geostationary Orbit (GSO) satellite, being 36000km away from the earth [2]. Due to these severe effects of degradation experienced by Ka-Band signal, it is expected that the availability of this signal would be best at least 99.9% or 99.7%, which means that the percentage of outage time is at 0.1% and 0.3% respectively [3].

There are many studies conducted to overcome this rain attenuation issue. Being concluded that fixed escalation of power could not be the practical solution due to wastage of energy during non-rainy days and tends to saturate, fade mitigation technique is proposed from the researchers of the field [4]. The fade mitigation technique suggests that site diversity is the most effective technique at region with high rainfall volume like tropical region [5]. Moreover, site diversity scheme could be a basis preparation for the use of higher frequency signal such as Q/V or perhaps W band in the future [6, 7].

The abundance of rain in tropical regions do not only causes attenuation, the signals can be lost at intervals, for short and sometimes in the long run depending on intensity and duration of rain [8]. The amount of rainfall distributed in Indonesia [9] and Nigeria [10] causes rainfall attenuation of up to 50 dB for 0.01% percentage over time, while in Malaysia, S.L. Jong et. al. [11] reported that the rain could incur attenuation as far as 80dB for Ka-Band frequencies at the same percentage of time for lower elevation angle. The differences in rain intensity at tropics and temperate region is supported by the rain events comparison made by Dalia Das and Animesh Maitra [12], between Kolkata at India and Spino d'Adda of Italy. The authors revealed that there are major differences in rain rate at 0.01% of time outage, with 100 mm/h in Kolkata and 10 mm/h in Spino d'Adda.

Site diversity is a concept to have another receiver at different places from the main, called diverse sites, receiving the same signal from the same satellites. The diverse site takes the advantage of inhomogeneous rainfall types in tropical region. Both two sites are connected to each other by terrestrial network or underground cables. When either sites receive stronger signals, that signal will be chosen and used for the applications at the main site [13]. There are two ways to define the effectiveness of site diversity scheme, that are through diversity gain and improvement factor, calculated either from raw data or predicted by a model. The diversity gain is defined as in equation (2).

$$A_j = \min\,(A_m\,, A_D) \qquad (1)$$

Where A_m is the attenuation at main site, A_D is the attenuation at diverse site, and A_j is the joint attenuation.

$$G_D = A_s - A_j \qquad (2)$$

Where G_D is the diversity gain, A_s is the attenuation of single site and A_j is the attenuation of joint distribution at the same percentage of time exceedance level.

A_j could be obtained from the equation (1) where at both sites' time series data, the highest signal of the same time between that sites (lowest attenuation) is selected to induce the joint attenuation value. However, due to the lack of availability of measurement data, Hodge, D.B. proposed an empirical model to calculate the diversity gain [14]. He introduced the factors that contribute to the total gain that are frequency, elevation angle, site separation distance and baseline orientation angle [15]. The author based on the 34 diversity experiments which was conducted in Canada, England, Japan and the United States, with frequencies ranged from 11.6 to 30 GHz, separation distances from 1.7 to 46.9 km, elevation angle from 10.7° to 55° and baseline orientation angle from 0° to 164° which was then scaled to 0° to 90° respectively [16]. Hodge Model is the multiplication of all factors that contribute to the sites' achievement as in equation (3). The model was adapted into ITU-R P. 618-13 documentation guideline with slight modifications in models' coefficients to satisfy the ITU-R databank [17].

$$G_D = G_d\, G_f G_\theta G_\varphi \qquad (3)$$

Where G_d is the gain from distance, G_f is the gain obtained from frequency, G_θ is the gain from elevation angle and G_φ is the gain from baseline orientation angle.

The improvements of Hodge Model have been raising from past years to accommodate the site locations' climate features.The factors that contributes to the gain are yet to be ascertained from the researchers in this field. Site separation apparently gives a major impact to the gain. The farther the separation distance between sites, the higher the gain because of different rain cell structure of each sites. A.D. Panagopoulos et al. [18] suggested that the site separation distance should have greater impact to the gain, thus proposing a new model like Hodge but differ in attributes. The author did the multiplication of the factors by highlighting attenuation at single site gain and site separation distance gain as major factors than others. Therefore, the diversity gain proposed by the author would be as in equation (4), with different coefficients than Hodge's.

$$G_D = G_A G_d\, G_f G_\theta G_\varphi \qquad (4)$$

Where G_A is the gain from attenuation at single site.

Frequency variability gives differences in attenuation, especially when the gap of frequency band is far. For example, it is known that the Ka-band signal is affected by rain twice as much as Ku-band, therefore the gain generated for the operation using Ka-band signals may be less than Ku-Band. However, as in tropical region, Yeo, Lee & Ong [19] reported that the diversity gain is independent of frequency and baseline orientation angle as well. The gain is claimed to hold on site separation distance, elevation angle and wind direction. However, the authors' latest discovery in [20] stated that the wind direction is dependent on the location. With that, they proposed a model that were based on 2025 paths database of grid divided locations in Singapore excluding the frequency contribution and the baseline angle, namely X.Yeo model. Semire et al. [21] agreed with Yeo, Lee & Ong regarding the independency of gain on frequency and baseline orientation angle. However, in year 2015, he proposed a new diversity gain model that similar with Hodge Model (with frequency and baseline angle gain contribution) structure. The model was improving Hodge's that was claimed to suit only site separation distance of less than 10km and lower elevation angle [21,22]. Semire model was induced from measurement attributes from five locations of tropical region. The sites are at different countries in Southeast Asia, namely Malaysia, Philippines, Fiji, Indonesia and Thailand [22].

To obtain the least resemblance of attenuation, the diverse site baseline angle should be at optimum value of 90°. However, K. Isiah Timothy [23] proves that the lowest as 4° baseline angle was a possible value in tropical region, due to the inhomogeneity of rainfall events and smaller raincell distance of this region. Another gain contributor includes elevation angle. When the angle is set higher, the distance between the satellite signal to the receiving antenna becomes shorter, thus reducing the possibility to stampede to rainfall events along the way to reach the destination on the earth, rather than the lower elevation angle. Qing Wei Pan et al. [24] mentioned in their article that a 5dB attenuation improvement could be obtained with higher angle.

However, despite having all the debate in mind, there are uncertainty in model's performance. This has been proven when a comparison was performed between ITU-R, Hodge, Panagopoulos and Semire model using local rain intensity at Malaysia [25], that in overall all models are underestimate the gain at tropical region at baseline angle of 0° and elevation angle of 77.4°. Another comparison was made also using rain intensity at four locations of Nigeria [26], which shows that ITU-R model overestimated the gain.

It is therefore important to investigate the reactivity of each model to these four mentioned factors. The main objective of this paper is to observe the selected model's sensitiveness towards frequency, elevation angle, baseline orientation angle and site separation distance. The importance of this knowledge is to guide the researchers to the use of the models to get the predicted gain, when implementing the site diversity scheme. Moreover, the knowledge is useful for researchers during development of more dynamic site diversity gain prediction model. The table of model's sensitiveness were highlighted at the end of this paper. The next section explains the methodology of the experimental work to assess the models, then section 3 is presenting the results and discussion of the work done. The last part is the conclusion from the result obtained.

2. RESEARCH METHOD

An investigation of five chosen models' attributes particularly that accommodating tropical region features has been conducted. The model of Hodge was redeveloped as in equation (5) to (11), as such can be referred in his article [15]. While the ITU-R's model preserves the structure of Hodges' as can be referred in [17], the model uses the same equation as in (5) and (6) but differs in coefficients a and b, such that in equation (12) and (13) respectively. The coefficient values for gain of frequency, G_f, gain of elevation angle, G_θ as well as baseline angle, G_φ are also different, highlighted as in equation (14),(15) and (16) respectively.

$$G_{SD} = G_d G_f G_\theta G_\varphi \tag{5}$$

With:

$$G_d = a(1 - e^{-bd}) \tag{6}$$

Where: $$a = 0.64A – 1.6(1\text{-}e^{-0.11A}) \tag{7}$$

$$b = 0.585(1\text{-}e^{-0.098A}) \tag{8}$$

$$G_f = 1.64\, e^{-0.025f} \tag{9}$$

$$G_\theta = 0.004920\theta + 0.834 \tag{10}$$

$$G_\varphi = 0.00177\varphi + 0.887 \tag{11}$$

Where d is the separation distance, a and b is the coefficient of the equation, A is the single site attenuation, f is the frequency of the signal, θ is the elevation angle and φ is the baseline orientation angle.

$$a = 0.78A – 1.94(1\text{-}e^{-0.11A}) \tag{12}$$

$$b = 0.59(1\text{-}e^{-0.1A}) \tag{13}$$

$$G_f = e^{-0.0025f} \tag{14}$$

$$G_\theta = 1 + 0.006\theta \tag{15}$$

$$G_\varphi = 1 + 0.002\varphi \tag{16}$$

Panagopoulos Model, as can be found in [18], stressed on the distance, so the coefficients of the factors that contributed to the gain are also differ from Hodges' and ITU-Rs'. With reference to equation (4), the consequent coefficients are such that in equation (17) to (21). It is important to highlight here that the three models discussed above use data sets from temperate regions. X.Yeo model, as can be referred in [20], excluded the gain from frequency and baseline angle, so the model is simpler than the Hodges' variation of models, such that in equation (22). Semire model resembles Hodges', the model preserves the equation of (5) and (6) but with different values of a and b, as such in equation (23) and (24), respectively. The model used different coefficients values for G_f, G_θ and G_φ so that to adapt for tropical region's climate features as highlighted in the author's article [22] such that in equation (25) to (27).

$$G_{A_s} = 8.19{A_s}^{0.0004} + 0.1809A_s - 8.2612 \quad (17)$$
$$G_d = \ln(3.6101d) \quad (18)$$
$$G_f = e^{-0.0006f} \quad (19)$$
$$G_\theta = 1.2347(1 - \theta^{-0.356}) \quad (20)$$
$$G_\varphi = 1 - 0.0006\varphi \quad (21)$$
$$G_{SD} = (-0.78 + 0.88A_s)(1 - e^{-0.18d})(1 + e^{-0.14\theta}) \quad (22)$$
$$a = 0.7755A + 0.3374\,(1 + e^{-9.16A}) \quad (23)$$
$$b = 0.1584(1 + e^{-0.03164A}) \quad (24)$$
$$G_f = 1.006e^{-0.0015f} - 0.395e^{-0.473f} \quad (25)$$
$$G_\theta = 0.899(1 + \theta^{-0.683}) \quad (26)$$
$$G_\varphi = -0.0000015\varphi + 0.9877 \quad (27)$$

A simulation environment was set-up using EXCEL, and the predefined parameters that was used during this testing was the configuration set-up of propagation experiment at Rawang and Cyberjaya. The frequency was initially set to 20.2GHz, with elevation angle of 68.8° and vertical polarization, baseline orientation angle of 65° and site separation distance of 42.52 km. The sample attenuation data used was an average measurement of year 2014 to 2017. The average attenuation used as one of the inputs to the model was fixed throughout the simulation. During the testing, the frequency was conditionally changed to 12.255 GHz (Ku Band), distance of 10 km, elevation angle of 25° and baseline angle of 4°. All the selected models were inserted various factors' values according to the predefined combinations such as the flow in Figure 1. Since there are four factors involves, the possible combinations were calculated as 2^4 which was 16 in total. This combinations were the testing lists that were performed in the analysis. With reference to Figure 1, HEA stands for Higher Elevation Angle, LEA for Lower Elevation Angle, HPhi for Higher Baseline Angle and LPhi for Lower Baseline Angle.

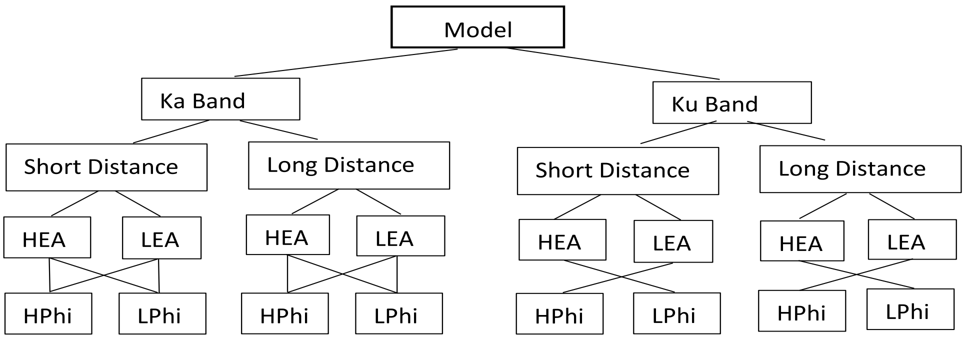


Figure 1. The flow of testing set

Table 1. Parameter setting for models' testing

Parameter	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8
Frequency (GHz)	20.2	12.255	20.2	12.255	20.2	12.255	20.2	12.255
Distance (km)	42.52	42.52	10	10	42.52	42.52	10	10
Elevation angle (°)	68.8	68.8	68.8	68.8	25	25	25	25
Baseline angle (°)	65	65	65	65	65	65	65	65

Table 2. Parameter setting for models' testing (continued)

Parameter	Set 9	Set 10	Set 11	Set 12	Set 13	Set 14	Set 15	Set 16
Frequency (GHz)	20.2	12.255	20.2	12.255	20.2	12.255	20.2	12.255
Distance (km)	42.52	42.52	10	10	42.52	42.52	10	10
Elevation angle (°)	68.8	68.8	68.8	68.8	25	25	25	25
Baseline angle (°)	4	4	4	4	4	4	4	4

$$\text{Percentage of change} = \frac{Gain_{first\ set} - Gain_{second\ set}}{Gain_{first\ set}} \text{ x } 100 \quad (28)$$

Where $Gain_{first\ set}$ is the gain predicted by the model using the first set of parameters, which has a fixed contributor's value except the observed contributors, such as previously mentioned examples, $Gain_{second\ set}$ is the gain predicted by the model using the second set of parameters, which has equal contributor's value as the first set, except the observed contributors is changed to other values, as mentioned beforehand.

The list of testing's values was displayed as in Table 1 and Table 2. Each model's progression was compared according to the changes of each factor. For example, to examine the sensitivity model against distance, distance values were changed from 42.52km to 10km. The first set of comparisons was that which has a distance value of 42.52km and the second set was the one with 10km, with both sets have the same value for other parameters. Therefore, for this comparison example, with reference to Table 1, set 1 was compared with set 3 (please notify the difference in the value of distance). Therefore, the percentage of change was calculated as in equation (28), where the predicted gain of the first set; $Gain_{first\ set}$ (which was set 1 in this case) and the predicted gain of the second set; $Gain_{second\ set}$(set 3 in this case) were collected at 0.01 percentage of time exceedance for each model. These second predicted gain were deducted to the first predicted gain, to observe the percentage of difference from the original setting (first set).

The percentage of increment (positive value) or decrement (negative value) of the consequent predicted gain value caused by the changes of the factors by all models as calculated in equation (28) was chosen such that to ease the comparison between models. Moreover, the excess or the reduced amount of the impacted gain values that were resulted from the change of each contributors could be evaluated. The changes of gain of each models portrayed the characteristics of the models as described in [19,21]. The value of each contributors could be varied depending on the configuration of local testing environment. The percentage of change (excessiveness/reduction) that could be observed using other values than this experiment would be different, however, it does not change the sensitiveness outcome of each models.

Subsequently, after comparing set 1 and set 3, the sensitiveness to distance was observed more using set 2 against set 4 (notify the difference in frequency than set 1 and set 3), set 5 with set 7 (notify the difference in elevation angle than set 1 and set 3) , set 6 with set 8 (notify the difference in frequency and elevation angle than set 1 and set 3), set 9 and set 11 (notify the difference in baseline angle than set 1 and set 3), set 10 and set 12 (notify the differences in frequency and baseline angle than set 1 and set 3), set 13 and set 15 (notify the differences in elevation and baseline angle than set 1 and set 3), and finally set 14 and set 16 (notify the differences in frequency, elevation and baseline angle than set 1 and set 3). These comparisons were conducted thoroughly so that all the possible conditions could be covered. The same procedure was applied to the other three factors; the elevation angle, the frequency and the baseline orientation angle. Each of them has a comparable number of 8, so overall constituted 32 comparisons for all four factors.

3. RESULTS AND DISCUSSION

The testing started with the default value as in Set 1. All models were set with this parameter as can be seen in Figure 2(a). Then, the factors' value was changed accordingly, so they were evaluated as in the next subsection. Please be noted that the results displayed in this article have been rounded to four decimal value, therefore kindly allow a bit variation in the calculation of percentage of change. Model of Panagopoulos was shortformed to Pana- to ease the reading and comparison. In this section, all the analysis of the models' predicted gain comparison was made specifically at 0.01% of time exceedance.

3.1. Frequency Dependency

The frequency was changed from Ka-Band (20.2 GHz) to Ku-Band (12.255 GHz) and all sets reflected with this change were compared. The results were displayed as in Figure 2 and Figure 3. From Figure 2, the changes of graph from set 1 to set 2 can be obviously seen. Hodge model predicted more gain at lower frequency compared to others. This is to reflect the concept that attenuation at lower frequency is smaller than the higher frequency, in this case Ka-Band. Therefore, the gain is predicted high. Other models did not present the obvious change, so the calculation of percentage of change is deemed important so that to trace even the smallest changes.

In Figure 3, the change of frequency from set 3 of 20.2 GHz in (a) to 12.255GHz in (b) was came along with the changes in distance. However, the distance value was set constant for both set to see the effect of models upon changes of frequency at lower site separation distance. The effect was displayed in Figure 3(a) for set 3 and Figure 3(b) for set 4. The graph of Figure 3(a) with short distance value of 10km, apparently different than Figure 2(a) which was set at 42.52km. There was a great change of gain predicted by Hodge model in Figure 3(b) compared to Figure 3(a). In this case also, other models did not show obvious change of gain at 0.01 percentage of time. The rest of other graph of comparisons showed the same pattern, and for the sake of being brief, the graph was not shown here. However, from the calculation of percentage of changes that was revealed in Table 3, it was observed surprisingly that the percentage of changes were the same throughout all eight comparisons. Therefore, it could be concluded from this experiment that, the movement of change of the predicted gain of each model towards frequency variations are consistent though in short distance and lower elevation and baseline angle.

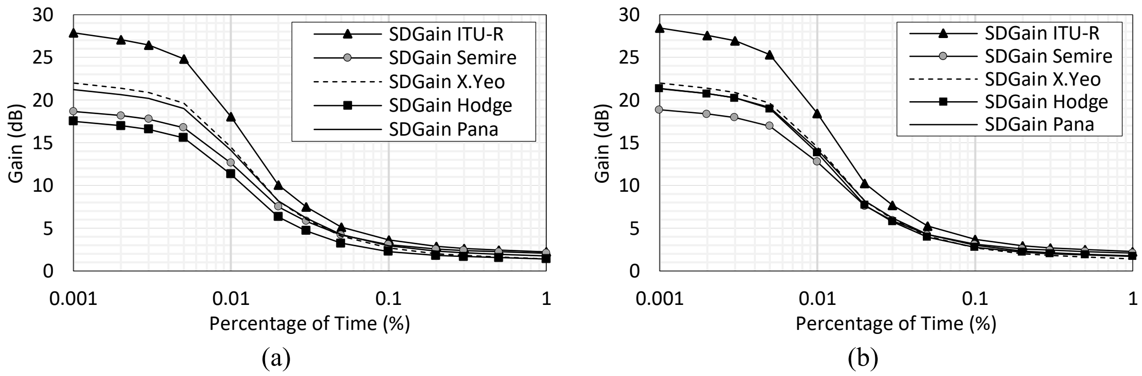


Figure 2. Performance of models on frequency changes, from Ka-Band to Ku-Band with distance of 42.52km and other parameters were fixed such that (a) Set 1 vs (b) Set 2

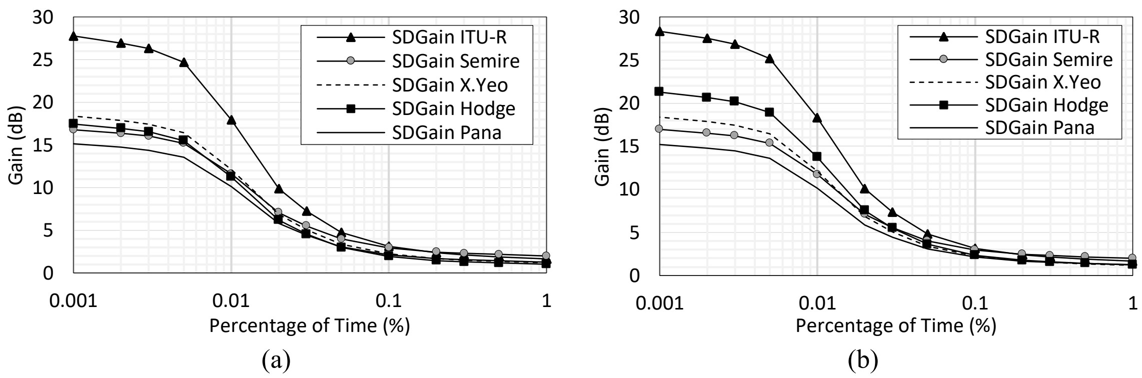


Figure 3. Performance of models on frequency changes, from Ka-Band to Ku-Band with distance of 10km and other parameters were fixed, such that (a) Set 3 vs (b) Set 4

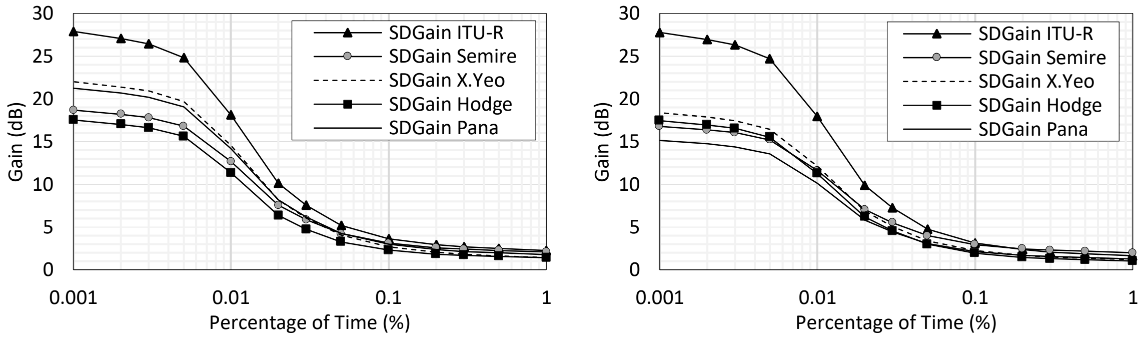
With reference to the outcome percentages of changes in Table 3, all models increased the gain with certain percentage except X. Yeo models. This is because the gain prediction of X. Yeo model was designed not to rely on signal frequency. Hodge portrayed the largest percentage of change in predicted gain with 21.97% increment, ITU-R model 2.006%, Semire 1.0788% while Panagopoulos portrayed the least affected by the changes of frequency, which was 0.4778%. Specifically, the transition of predicted gain by Hodge model was from 11.36 dB in Figure 2(a) to 13.86 dB in Figure 2(b) at 0.01% of time exceedance. While in Figure 3(b) was 11.26 dB then, the gain was increased to 13.74 dB in Figure 3(b), as can be observed in Table 7 and Table 8. Hence, it is obviously seen that with this percentages that far higher than other models, Hodge model is proven to be more sensitive to frequency than others, then followed by ITU-R and Semire models. Panagopoulos was considered slightly sensitive to frequency because of a very small changes on the gain prediction value.

Table 3. Percentage of change (%) in predicted gain on each set against frequency

Models	set 1 vs set 2	set 3 vs set 4	set 5 vs set 6	set 7 vs set 8	set 9 vs set 10	set 11 vs set 12	set 13 vs set 14	set 15 vs set 16
ITU-R	2.006	2.006	2.006	2.006	2.006	2.006	2.006	2.006
Semire	1.0788	1.0788	1.0788	1.0788	1.0788	1.0788	1.0788	1.0788
X.Yeo	0	0	0	0	0	0	0	0
Hodge	21.972	21.972	21.972	21.972	21.972	21.972	21.972	21.972
Pana-	0.4778	0.4778	0.4778	0.4778	0.4778	0.4778	0.4778	0.4778

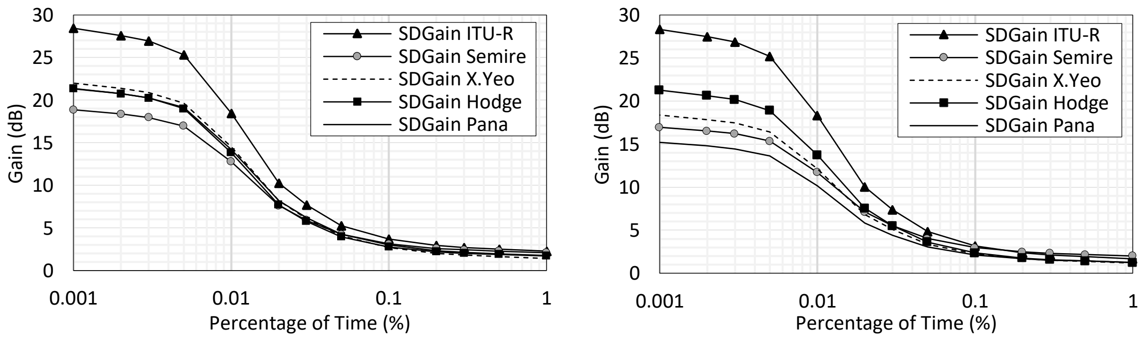
3.2. Distance Dependency

Then, the site separation distance was lowered from 42.52 km to 10 km and the related sets were compared. The results portrayed the same percentage of changes throughout the 8 comparisons. Therefore, for the sake of observation to the graph variations thus set 1 and set 3 were chosen to be an example of comparison as displayed in Figure 4(a) and Figure 4(b) respectively. From visual inspection of these figures, X. Yeo and Panagoupolos (a.k.a Pana) models were showing a decrease in predicted gain obviously, from 14.52 dB to 12.13 dB and from 14.17 dB to 10.096 dB at 0.01% of time respectively.



(a) (b)

Figure 4. Performance of models on changes of distance, from 42.52km to 10km of Ka-Band while other parameters were fixed, such that in (a) Set 1 vs (b) Set 3



(a) (b)

Figure 5. Performance of models on changes of distance, from 42.52km to 10km of Ku-Band while other parameters were fixed, such that in (a) Set 2 vs (b) Set 4

Figure 5 displayed the comparison of set 2 in (a) and set 4 in (b). This comparison was to observe how the models react for the change of distance at lower frequency, Ku-Band. Apparently, X. Yeo and Panagopoulos graphs showed a great movement of lowering down the predicted gain. The same characteristics was shown for all eight testing lists, therefore the percentage of change in Table 4 was induced. So, the changes were seen consistent in any environment as what has been concluded from section 3.1. From Table 4, the great impact of gain decrement could be seen in Panagopoulos, X. Yeo and Semire models, with 28.75%, 16.49% and 8.227% than Hodge and ITU-R Model which are 0.8339% and 0.7716% respectively.

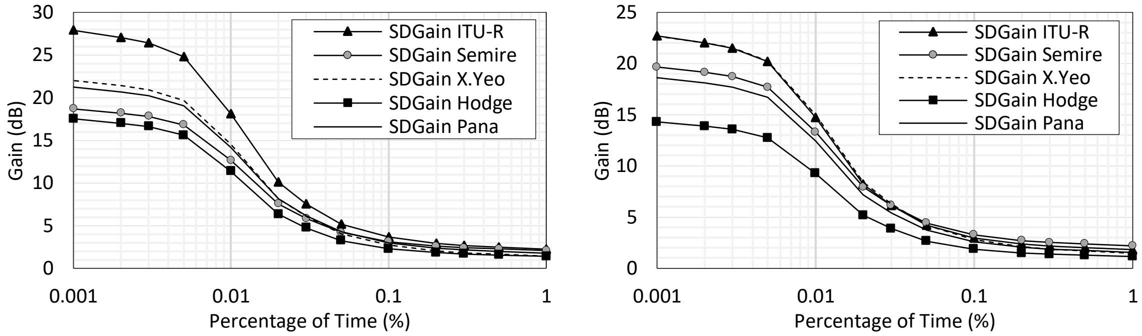
Therefore, Panagopoulos, X. Yeo and Semire models are viewed as more sensitive towards the change of distance, while Hodge and ITU-R model are not, because of unnoticeable graph change in gain prediction as can be observed in Figure 4 and Figure 5 and the gain value as revealed in Table 7 and Table 8.

3.3. Elevation Angle Dependency

The value of elevation angle was changed from 68.8° to 25°. The related sets were compared and the percentage of changes at 0.01% of outage time were noted as in Table 5. The example graph of this change was depicted in Figure 6(a), which was of set 1, comparing with set 5 of Figure 6(b).

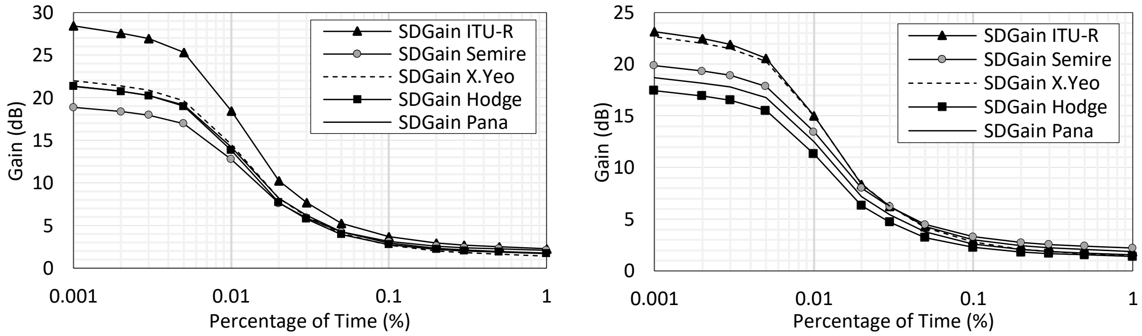
Table 4. Percentage of change in predicted gain on each set against separation distance

Models	set 1 vs set 3	set 2 vs set 4	set 5 vs set 7	set 6 vs set 8	set 9 vs set 11	set 10 vs set 12	set 13 vs set 15	set 14 vs set 16
ITU-R	-0.7716	-0.7716	-0.7716	-0.7716	-0.7716	-0.7716	-0.7716	-0.7716
Semire	-8.227	-8.227	-8.227	-8.227	-8.227	-8.227	-8.227	-8.227
X.Yeo	-16.49	-16.49	-16.49	-16.49	-16.49	-16.49	-16.49	-16.49
Hodge	-0.8339	-0.8339	-0.8339	-0.8339	-0.8339	-0.8339	-0.8339	-0.8339
Pana-	-28.754	-28.754	-28.754	-28.754	-28.754	-28.754	-28.754	-28.754



(a) (b)

Figure 6. Performance of models on changes of elevation angle, from 68.8° to 25° of Ka-Band while other parameters were fixed, such that in (a) Set 1 vs (b) Set 5



(a) (b)

Figure 7. Performance of models on changes of elevation angle, from 68.8° to 25° of Ku-Band while other parameters were fixed, such that in (a) Set 2 vs (b) Set 6

From the graph of Figure 6(b), the result portrayed an increase of predicted gain of Semire and X. Yeo's model, with 5.247% and 3% of increment respectively, compared to set 1 in Figure 6(a). Panagopoulos, Hodge and ITU-R Model lowered the gain by 12.36%, 18.379% and 18.6% respectively. The same increment of predicted gain was also detected in Figure 7 for Semire and X. Yeo model, while Hodge, ITU-R and Panagopoulos model decreased the predicted gain, when Ku-Band environment was applied.The same models reactivity feature was also observed at lower baseline angle and distance, and the rest of all related testing sets, as shown in the percentage of change in Table 5.

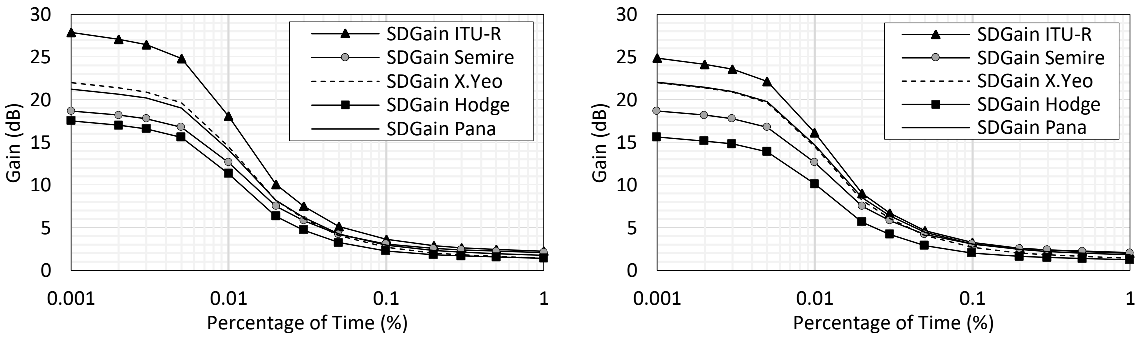
According to Qing Wei Pan et al. [24], the attenuation is higher at lower elevation angle, therefore this condition will make the diversity gain lower because the difference between single site attenuation and joint attenuation is reduced, as experimented by Hodge, D.B. [15] as well. From this observation, Semire and X. Yeo does not response right to the elevation angle property because they tend to increase the gain instead of decreasing. However, Semire and X. Yeo model was left to be concluded as also sensitive to the elevation angle but with opposite direction. Therefore, it was concluded that Panagopoulos, Hodge and ITU-R Model respond to the requirement quite well.

Table 5. Percentage of change in predicted gain on each set against elevation angle

Models	set 1 vs set 5	set 2 vs set 6	set 3 vs set 7	set 4 vs set 8	set 9 vs set 13	set 10 vs set 14	set 11 vs set 15	set 12 vs set 16
ITU-R	-18.6014	-18.6014	-18.6014	-18.6014	-18.6014	-18.6014	-18.6014	-18.6014
Semire	5.24728	5.24728	5.24728	5.24728	5.24728	5.24728	5.24728	5.24728
X.Yeo	3.01298	3.01298	3.01298	3.01298	3.01298	3.01298	3.01298	3.01298
Hodge	-18.3792	-18.3792	-18.3792	-18.3792	-18.3792	-18.3792	-18.3792	-18.3792
Pana-	-12.3613	-12.3613	-12.3613	-12.3613	-12.3613	-12.3613	-12.3613	-12.3613

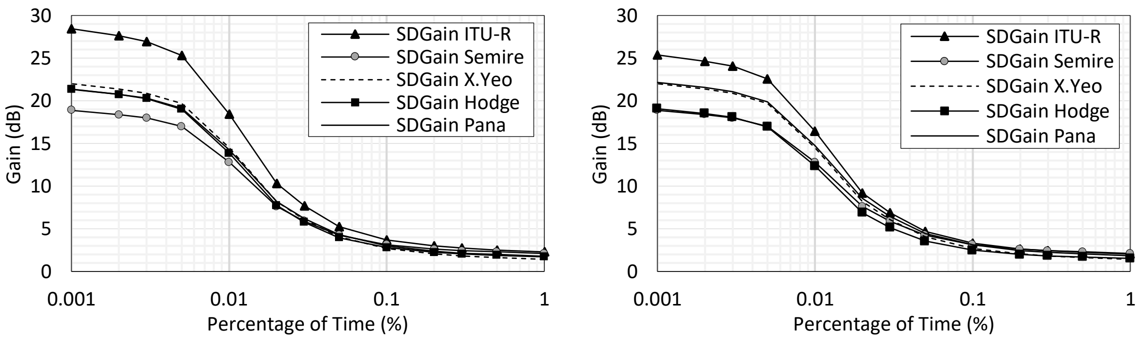
3.4. Baseline Angle Dependency

The baseline orientation angle was lowered from 65° to 4°. The resultant graph was displayed in Figure 8 which was comparing set 1 in (a) and set 9 in (b) of Ka-Band. The predicted gain from ITU-R and Hodge model were decreased as can be seen at Figure 8(a) then Figure 8(b), while X. Yeo model seems to hold the same value of gain. Panagopoulos and Semire model apparently showed a bit increase in the gain prediction. Figure 9 was comparing set 2 and set 10 of Ku-Band. A great change of gain can be observed in graph of ITU-R and Hodge which lowered the gain. While Panagopoulos and Semire model slightly increased a little bit of predicted gain, that were almost unnoticeable. All the rest of resultant graph were showing equal models' sensitivity towards baseline angle changes despite of being tested throughout related testing lists.



(a) (b)

Figure 8. Performance of models on changes of baseline angle, from 65° to 4° of Ka-Band while other parameters were fixed, such that in (a) Set 1 vs (b) Set 9



(a) (b)

Figure 9. Performance of models on changes of baseline angle, from 65° to 4° of Ku-Band while other parameters were fixed, such that in (a) Set 2 vs (b) Set 10

From the observation of the graph in Figure 8(b) and Figure 9(b), Semire and Panagopoulos model estimated a little higher gain compared to Figure 8(a) and Figure 9(a) respectively with their constantly incremental percentage of 0.009% and 3.809% respectively. However, baseline orientation angle gives much influence on the gain estimated by Hodge and ITU-R model. Hodge model lowered the gain as much as 10.775% and ITU-R model was 10.796%. Yeo Model did not affect totally by this changing environment because the model does not bother about the angle. However, according to Ippolito J.L. Jr [2], the chances to intersect the same rain event is higher when the baseline angle is lower with respect to the main sites, which makes the diversity gain lowered because of the similar attenuation experienced. From this point of view, Hodge and ITU-R Model suits the concept while Panagopoulos and Semire did not. Therefore, Hodge and ITU-R model is considered as sensitive to the baseline angle, while Semire did not. Panagopoulos model is also considered to sensitive to the baseline angle changes, but with opposite direction of supposedly it should be reacted. The same goes with the comparison of all sets, the percentages of change were the same and the result was displayed Table 6.

Table 6. Percentage of change in predicted gain on each set against baseline angle

Models	**set 1 vs set 9**	**set 2 vs set 10**	**set 3 vs set 11**	**set 4 vs set 12**	**set 5 vs set 13**	**set 6 vs set 14**	**set 7 vs set 15**	**set 8 vs set 16**
ITU-R	-10.796	-10.796	-10.796	-10.796	-10.796	-10.796	-10.796	-10.796
Semire	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093	0.0093
X.Yeo	0	0	0	0	0	0	0	0
Hodge	-10.775	-10.775	-10.775	-10.775	-10.775	-10.775	-10.775	-10.775
Pana-	3.809	3.809	3.809	3.809	3.809	3.809	3.809	3.809

Table 7 and Table 8 shows the exact value of each models' predicted gain at 0.01% of outage time resultant from all the setting arrangements. From the observation of experimented data, the models' sensitiveness upon major factors that influence the diversity gain is summarized in Table 9.

Table 7. Diversity Gain of each models for each setting at 0.01% of outage time

Models	**Set 1**	**Set 2**	**Set 3**	**Set 4**	**Set 5**	**Set 6**	**Set 7**	**Set 8**
ITU-R	18.0899	18.4528	17.9503	18.3104	14.7249	15.0203	14.6113	14.9044
Semire	12.6505	12.7869	11.6096	11.7349	13.3143	13.4579	12.2188	12.3506
X.Yeo	14.5261	14.5261	12.1307	12.1307	14.9637	14.9637	12.4962	12.4962
Hodge	11.3634	13.8602	11.2687	13.7446	9.2749	11.3128	9.1976	11.2185
Pana-	14.1714	14.2391	10.0966	10.1448	12.4196	12.4790	8.8485	8.8908

Table 8. Diversity Gain of each models for each setting at 0.01% of outage time (continued)

Models	**Set 9**	**Set 10**	**Set 11**	**Set 12**	**Set 13**	**Set 14**	**Set 15**	**Set16**
ITU-R	16.1368	16.4605	16.0123	16.3335	13.1351	13.3986	13.0338	13.2953
Semire	12.6516	12.7881	11.6107	11.7360	13.3155	13.4591	12.2199	12.3518
X.Yeo	14.5261	14.5261	12.1307	12.1307	14.9637	14.9637	12.4962	12.4962
Hodge	10.1390	12.3668	10.0545	12.2637	8.2755	10.0939	8.2065	10.0097
Pana-	14.7111	14.7814	10.4811	10.5312	12.8926	12.9542	9.1855	9.2294

Table 9. Sensitivity of each model towards Frequency, Distance, Elevation angle and Baseline Angle

Model	**Sensitivity**			
	Frequency	**Distance**	**Elevation Angle**	**Baseline Angle**
Hodge Model	Yes	No	Yes	Yes
ITU-R Model	Yes	No	Yes	Yes
Semire Model	Yes	Yes	Yes	No
X.Yeo Model	No	Yes	Yes	No
Panagopoulos Model	No	Yes	Yes	Yes

4. CONCLUSION

In this article we discussed on how each site diversity model is influenced by four contributing factors, that are frequency, elevation angle, base line angle and separation distance. Models that have been analyzed were of Hodge's, ITU-R's, Panagopoulos's, Semire and X.Yeo's. It was found that, Hodge and ITU-R models had weaknesses which were not so sensitive to the separating distance, giving low gain predictions and increasingly saturated as the distance went further. While X.Yeo do not sensitive to frequency at all and Panagopoulos model is considered do not sensitive to frequency due to very small percentage of changes detected. Semire model is considered not sensitive to baseline angle changes because of very small percentage of changes shown and Panagopoulos models are considered slightly sensitive to the baseline angle, but with opposite direction than what the gain should be. The same goes when the elevation angle was lowered down. Semire and X.Yeo models slightly increase the gain where they should decrease it because of lower angle caused more attenuation than higher angle. It can thus be conclusively concluded that there has not been any model that really conforms to the dynamics concepts that should exist for a reliable model that can be used directly by users who want to get an idea of the diversity scheme's capabilities to be implemented. It is suggested that the study of contributing factors to the value of this predictive gain gets the focus particularly on tropical features.

REFERENCES

[1] A.D. Panagopoulos, P.D.M. Arapoglou, and P.G. Cottis, “Satellite communications at KU, KA, and V bands: Propagation impairments and mitigation techniques,” *IEEE Communications Surveys & Tutorials*, vol. 6, no. 3,pp. 2-14, 2004. DOI: 10.1109/COMST.2004.5342290.
[2] J. L. Jr. Ippolito, *Satellite Communications System Engineering. Atmospheric Effects, Satellite Link Design and System Performance*, 2nd ed. West Sussex,UK: John Wiley and Sons Ltd, 2017.
[3] ITU-R Radiocommunication Sector of ITU, Recommendation ITU-R P.679-4 (07/2015), Propagation data required for the design of broadcasting-satellite systems, *Electronic Publication*, Geneva. 2015.
[4] L. Castanet, A. Alamañac, Bousquet, and Michel, “Interference and Fade Mitigation Techniques for Ka and Q/V Band Satellite Communication Systems,” https://www.researchgate.net/publication/228608295-Interference-and-Fade-Mitigation-Techniques-for-Ka-and-QV-Band-Satellite-Communication-Systems, 2003 [accessed 30 June 2019].
[5] F. Cuervo, *et al.*, "Ka-Band Propagation Campaign in Malaysia-First Months of Operation and Site Diversity Analysis, " in *10th European Conference on Antennas and Propagation (EuCAP)*, 2016, pp.1–5.
[6] A. Kyrgiazos, B. Evans, and P. Thompson, “On the gateway diversity for high throughput broadband satellite systems,” *IEEE Transactions on Wireless Communications*, vol.13, no.10, pp.5411–5426. DOI: 10.1109/TWC.2014.2339217.
[7] H. Fenech, *et al.*, "An Operator’s Perspective on Propagation," in *8th European Conference on Antennas and Propagation (EuCAP)*, 2014, pp.3349-3352. DOI: 10.1109/EuCAP.2014.6902545.
[8] I. Md. Rafiqul, *et al.*, "Analysis of Rain Fade Mitigation using Site Diversity on Earth to Satellite Microwave Links at Ku-Band," in *5th Brunei International Conference on Engineering and Technology (BICET 2014)*, 2014, pp.1-5. DOI: 10.1049/cp.2014.1104.
[9] P.Oxy Riza, *et al*.,"Implementation Site Diversity Method on Ka-band Satellite to Reduce the Impact of Rain Attenuation in the Tropics Area, "in *International Conference on ICT for Smart Society*, 2013, pp.1-6.
[10] O. Achor Jane, M. Udofia Kufre, and B. Obot Akaninyene, “Seasonal variations of site diversity along earth-space paths in Nigeria,” *International Journal of Information and Communication Sciences*, vol.1, no. 3, pp. 54-58, 2016. DOI: 10.11648/j.ijics.20160103.14.
[11] S.L.Jong, H.Y. Lam, J. Din, and M. D'Amico., “Investigation of Ka-band satellite communication propagation in equatorial regions,” *ARPN Journal of Engineering and Applied Sciences*, vol.10. no. 20, pp. 9795-9799, 2015.
[12] Dalia Das, and Animesh Maitra, “Rain attenuation prediction during rain events in different climatic regions,” *Journal of Atmospheric and Solar-Terrestrial Physics*, vol.128, pp. 1-7, 2015. DOI: 10.1016/j.jastp.2015.03.003.
[13] D. V. Rogers, and J. E. Allnutt, "Evaluation of a Site Diversity Model for Satellite Communications Systems, " in *Communications, Radar and Signal Processing, IEE Proceedings F*, vol. 131, no. 5, pp. 501-506, 1984. DOI: 10.1049/ip-f-1.1984.0076.
[14] D.B. Hodge, “An empirical relationship for path diversity gain,” *IEEE Transactions on Antennas and Propagation*, vo. 24, no. 2, pp. 250–251, 1976. DOI: 10.1109/TAP.1976.1141304.
[15] D.B. Hodge, “ An improved model for diversity gain on earth-space propagation paths,” *Radio Science. AGU Journals and Magazines*, vol.17, no. 6, pp. 1393-1399, 1981.
[16] A.V. Bosisio, C. Capsoni, and E. Matricciani, "Comparison among prediction methods of site diversity system performances, " in *Eighth International Conference on Antennas and Propagation*, 1993, pp. 60-63.
[17] ITU-R Radiocommunication Sector of ITU, Recommendation ITU-R P.618-13 (12/2017). Propagation Data and Prediction Methods Required for the Design of Earth-Space Telecommunication Systems, *Electronic Publication*, Geneva, 2017.
[18] A. D. Panagopoulos, P. -D. M. Arapoglou, J. D. Kanellopoulos, and P. G. Cottis, “Long-term rain attenuation probability and site diversity gain prediction formulas,” *IEEE Transactions on Antennas and Propagation*, vol.53, no. 7, pp. 2307-2313, 2005. DOI: 10.1109/TAP.2005.850762.
[19] J. X. Yeo, Y. H. Lee, and J. T. Ong, “Performance of site diversity investigated through RADAR derived results,” *IEEE Transactions on Antennas and Propagation*, vol.59, no. 10, pp. 3890 – 3898, 2011. DOI: 10.1109/TAP.2011.2163770.
[20] J.X. Yeo, Y.H. Lee, and J.T. Ong, “Site diversity gain at the equator: Radar-derived results and modelling in Singapore,” *International Journal of Satellite Communications and Networking*, vol. 33, no. 2, pp. 107-118. 2015. DOI: 10.1002/sat.1074.

[21] F.A.Semire, M. Rosmiwati, I.Widad, M.Norizah, and J.S.Mandeep, "Evaluation of site diversity rain attenuation mitigation technique in South-East Asia," *Journal of Acta Astronautica. Science Direct,* vol. 96, no. 1, pp. 303-312, 2014. DOI: 10.1016/j.actaastro.2013.11.034.

[22] F.A.Semire, R. Mohd-Mokhtar, W.Ismail, N. Mohamad, and J.S.Mandeep, "Modeling of rain attenuation and site diversity predictions for tropical regions," *Journal of Annales Geophysicae,* vol. 33, no. 3, pp. 321-331, 2015. DOI :10.5194/angeo-33-321-2015.

[23] K.I. Timothy, Jin Teong Ong, and E.B.L. Choo, "Performance of the site diversity technique in Singapore: Preliminary Results," *IEEE Communications Letters*, vol.5, no. 2, pp. 49-51, 2001. DOI: 10.1109/4234.905932.

[24] Qing Wei Pan, Jeremy E. Allnutt, and Charles Tsui., "Evaluation of diversity and power control techniques for satellite communication systems in tropical and equatorial rain climates," *IEEE Transactions on Antennas and Propagation,* vol.56, no. 10, pp. 3293-3301, 2008. DOI: 10.1109/TAP.2008.929448.

[25] Md Rafiqul Islam, Ali Kadhim Lwas, and M. H. Habaebi., "Site diversity gain for earth-to-satellite links using rain intensity measurement," *Indonesian Journal of Electrical Engineering and Informatics*, vol.5, no. 4, pp.330-338, 2017. DOI: 10.11591/ijeei.v5i4.364.

[26] J. O. Achor, K. M. Udofia, and A. J. Jimoh, "Investigation of the performance of site diversity through rain gauge measurements in South-South Nigeria," *Journal of Mathematical and Software Engineering*, vol. 2, no. 2 pp. 105-113, 2016.

BIOGRAPHIES OF AUTHORS

Fazdliana obtained her first degree at Multimedia University, Cyberjaya, Selangor, Malaysia in year 2000 in Electronics, majoring in Computer Engineering. She worked in Telekom Malaysia Research & Development under various multimedia projects as an IT Engineer/Researcher. She graduated Master of Engineering in Computer and Communication in year 2018, hence pursuing her focus study on Satellite Communication by the end of the year for doctoral degree at Universiti Kebangsaan Malaysia (UKM).

Ir. Dr. Mandeep Singh Jit Singh is a Professor at Universiti Kebangsaan Malaysia (UKM), currently posting as a lecturer and head of Space Science Center (ANGKASA) at UKM. His focus interest research area are in prediction of propagation impairments on earth-space paths, RFID wireless sensor network for medical diagnosis, and engineering in education.. He is also hold an advisory post in the Institution of Engineers Malaysia.