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RESEARCH ARTICLE - ATMOSPHERIC & SPACE SCIENCES

Site diversity performance in Ka band using *a* 7.3-m antenna diameter at tropical climate: a comparison of prediction models

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Abstract
Site diversity gain prediction models were created to estimate mathematically the acquired benefits from the implementation of site diversity at place of choice. This work contributes to the comparison of existing gain prediction model to the gain of measured attenuation at Cyberjaya and Rawang, Malaysia. The experiment has been conducted for 4 years from 2014 to 2017, in Ka band using a large 7.3-m diameter antenna and a high elevation angle of 68.8°, together with the rain analysis at both places for the same duration. The average monthly rainfall and attenuation for 4 years were presented. The results revealed that prediction model Hodge performs better than other models, while X. Yeo and Panagopoulos models appear to exhibit very similar graph shape to the measured gain data. More research on gain development in tropical region should be conducted, as the existing prediction model appears to be less consistent with the current data.

Keywords Signal propagation · Atmospheric attenuation · Ka-band signal · Model comparison · Site diversity

Introduction

The trend of wireless communication is gearing to 5G network, which has capabilities of higher speed and larger bandwidth than earlier technology (4G). While terrestrial network is becoming a focus, satellite communication plays similar significant role to provide the requested future bandwidth capabilities, especially at unreachable area by the former. Ka band, Q/V band or even W band is a band of choice to provide this demand, because higher frequency corelates with higher capacity (Kyrgiazos et al. 2014). With high throughput satellite (HTS), this high capacity could be realized and resulted in consequent cost saving at roughly 30% per annum in view of satellite communication service provider (Callaghan et al. 2008). Unfortunately, the high frequency is easily being degraded by tropospheric precipitation and scintillation. However, the most impairment comes from rain, together with cloud formation that contributed to the attenuation of the signal. Nonetheless, the effect of cloud attenuation is seen around 2–4 dB, impacting the received signal from the satellite (Omotosho et al. 2011; Yuan et al. 2017). This formation of cloud and the correlated attenuation is observed severe for VSAT (very small aperture terminal) (Yuan et al. 2016) at longer slant path and low elevation angle (Yang et al. 2013). For the past years, many techniques have been proposed to mitigate this weather effects. Most of the experiments studied the effect of rain attenuation at Ka-band frequency, using temperate region databank. The experimental samples observed in this region showed that the attenuation at Ka band is more severe than Ku, at mostly double the effect (Panagopoulos et al. 2004).

Fade mitigation technique (FMT) proposed power control, adaptive coding modulation (ACM) and diversity techniques, as solutions depending on the purpose of the system application and requirement (Yussuff et al. 2017). However, since higher frequencies are expected to experience higher degree of signal degradations, so power control and ACM could no longer be applied (Rytir et al. 2017). Diversity itself is divided into four ways, namely frequency, time, satellite and site diversity. Among these techniques, site diversity (SD) is viewed as more efficient (Ippolito 2017). The

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concept of SD is to establish another receiver site at a separation of at least a rain cell at about tens of kilometers (Panagopoulos et al. 2005) to benefit from the inhomogeneity pattern of the rainfall. Both sites are receiving a signal from the same satellite, while the less attenuation sites will be chosen using selection combining or switching technique to be further process at the prime site (Rytir et al. 2017). This concept could be used together with ACM along the way after the selection has been made in case of severe condition of selected signal is still detected (Capsoni et al. 2009).

In tropical region, the number of SD studies is increasing recently. There are three types of data acquisition technique for SD investigation that have been conducted in the literature. One technique is using direct measurement from satellite (Acosta et al. 2012; Cuervo et al. 2016), another technique is using weather radar data (Yeo et al. 2011; Lam et al. 2015) and the third technique is using rainfall data (Islam et al. 2017; Harika et al. 2018). The propagation experiment to investigate the effectiveness of SD scheme in tropical region was first reported by Timothy et al. (2001), where he compared the local gain measurement of two sites separated by 12.3 km at Singapore with ITU-R SD gain model, using lowest claimed baseline orientation angle which was 4°. Another comparison study was conducted by Yeo et al. (2011), also was based in Singapore. He used radar data to compare Hodge and ITU-R gain model and thus concluded that Hodge model was not sensitive to separation distance, while ITU-R model overestimated the gain in tropical region. The experiment was conducted at18.9 GHz signal with elevation angle of 44.5°. Semire et al. (2014, 2015) investigated on SD link parameters at five different sites based in Malaysia, Indonesia, Philippines, Thailand and Fiji. The author compared Hodge, Panagopoulos and Nagaraja (2012) model at Ku-band signal, thus concluded that Hodge model is practical for separation distance below 10 km and Panagopoulos and Nagaraja models are best suited for temperate region. In year 2017, Islam et al. (2017) experimented SD scheme using rain attenuation deduced from rain intensity measurement. The SD gain models were analyzed using local data, which was at International Islamic University Malaysia and Faculty of Engineering, UKM, Malaysia, separated by 37 km. The comparison was made using elevation angle of 77.4°, frequency 12 GHz and baseline angle of 0° and 90°, between ITU-R, Hodge, Panagopoulos and Semire models (Islam et al. 2017). With this local measurement, ITU-R and Hodge model showed good agreement when using baseline angle of 90°, while Panagopoulos gives better prediction of SD gain when baseline angle of 0° was used. Semire model was observed to underestimate the gain for both 0° and 90° baseline angles, probably because this model was derived from a small-scale data test values of baseline angle.

This study is motivated by the lack of Ka-band SD scheme research in Malaysia and in general in tropical regions. To the best knowledge of the authors, in year 2015, there was a study on SD scheme using 20.245 GHz frequency at low degree of elevation angle; 25°, focusing on statistical analysis of rain fade dynamics (Jong et al. 2015). Therefore, there are less investigations on SD gain model at Ka band using direct measurement data from satellite with high elevation angle. From the comparison made by researchers in the literature, no prediction model shows consistency with the local data in tropical region. Therefore, the model proposed by scholars of the field particularly focusing on tropical region climate need to be evaluated using various local configurations. In addition, since the distance of raincell varies according to local terrain, the optimal exclusion zone for SD scheme should be considered to be as far as possible from the main site to avoid the same coming formation of coming cloud and rain caused by wind blow at nearby locality. SD gain prediction model is significant to assist the telecommunication engineer to estimate the capability of SD, before deploying the facilities. In other words, an effective investment can be performed by satellite operators if researchers can supply them with accurate and reliable tools to measure the level of SD technique, so that they can reduce costs and time to make decisions about the implementation of the scheme (Fenech et al. 2014).

This paper focuses on the SD gain obtained from live measurement of Ka-band signal at two separated location in west Malaysia with high elevation angle of 68.8° and large diameter of gateway antenna. The measured gain was compared with the empirical model developed by Hodge, Panagopoulos, Semire, X. Yeo, and ITU-R model as well. A brief description of each model is narrated at the next section, highlighting the differences of each other. Then, "Methods " is the methods of the measurement, showing that the factors that contribute to the attenuation, and "Results and discussions" discusses the results. Finally, a conclusion is drawn based on the results found.

Site diversity gain prediction models

Most common metric to measure the SD effectiveness is by calculating the gain and improvement factor. The SD gain is calculated as the difference between the attenuation of single site and attenuation of joint sites at the same percentage of probability of time exceedance. Due to scarce availability of measured data, two types of prediction methods are developed, which are physical and empirical model. This article focuses on empirical models, as it is more easily to be applied and provides faster results than physical models that require a comprehensive understanding of rain process, plus the difficulty of obtaining the data required to be used in the model (Yeo et al. 2015). The first empirical model was proposed in 1981 (Hodge 1981), an initiative from Hodge, that had started the research in early 1970's. It was an improvement from the earlier version

(Hodge 1976), highlighting the fourth factors that contributed to the SD gain, which was the link frequency, with more experimental data than the former. This newly improved model, namely Hodge's model was 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 from 0° to 90° (Bosisio et al. 1993; Hodge 1981). This model is a multiplicative of all gains contributed to the total overall site diversity gain, G_{SD}, that are frequency, G_f, baseline orientation angle, G_φ, elevation angle, G_θ and site separation distance, G_d as in (1).

$$G_{SD} = G_f G_\varphi G_\theta G_d, \tag{1}$$

With: $G_d = a\left(1 - e^{-bd}\right)$,
where: $a = 0.64A - 1.6(1 - e^{-0.11A})$,
$b = 0.585(1 - e^{-0.098A)}$,

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

$$G_\theta = 0.00492\theta + 0.834,$$

$$G_\varphi = 0.00177\varphi + 0.887.$$

The model was then adopted in ITU-R with a bit modification on the coefficient to suit the ITU-R databank (Ippolito 2017). ITU-R model can be obtained from the guideline document available (ITU-R P.618–13 2017). Hodge model had been compared with another empirical techniques as well namely Goldhirsh, Allnutt and Rogers, and CCIR and physical model, namely Mass, Matricciani and Capsoni et al. model using temperate region databanks (Bosisio et al. 1993). The result was in favor to Hodge model. Panagopoulos et al. (2005) identified that Hodge model was not sensitive to the separation distance and portray gain saturation at a distance more than 15 km. The gain was supposedly to increase proportionally to the distance due to higher decorrelation in rainfall events, which leads to unbalanced attenuation threshold at both sites. Therefore, the author proposed new coefficients to be used in the multiplication of the gain contributors, which is the addition of single site attenuation gain, such that in (2), so that it compensated the justified weaknesses of Hodge model, using temperate region database (Panagopoulos et al. 2005).

$$G_{SD} = G_{A_s} G_d G_f G_\theta G_\varphi \tag{2}$$

With: $G_{A_s} = 8.19{A_s}^{0.0004} + 0.1809A_s - 8.2612$,

$$G_d = \ln(3.6101d),$$

$$G_f = e^{-0.0006f},$$

$$G_\theta = 1.2347(1 - \theta^{-0.356}),$$

$$G_\varphi = 1 - 0.0006\varphi.$$

Semire et al. (2015) experimented SD using databank from tropical region of five distinct countries, namely Malaysia, Philippines, Indonesia, Thailand and Fiji. Hodge model has been analyzed using the tropical region data and it was found that the model showed less accuracy at lower elevation angle and high frequency. Therefore, the author proposed new expressions and coefficients involving low elevation angles from 10° to 50° and high frequency up to 70 GHz, while the model's structure is unchanged and in line with the Hodge model, such that in (3). This new prediction model was compared with the original Hodge, Panagopoulos and Nagaraja (2012) models and it was apparently deduced that Semire et al. model predicted well than others when tested on data of tropics.

$$G_{SD} = G_d G_f G_\theta G_\varphi, \tag{3}$$

With: $G_d = a\left(1 - e^{-bd}\right)$,
where: $a = 0.7755A + 0.3374\ (1 + e^{-9.16A})$,
$b = 0.1584(1 + e^{-0.03164A})$,

$$G_f = 1.006e^{-0.0015f} - 0.395e^{-0.473f},$$

$$G_\theta = 0.899(1 + \theta^{-0.683}),$$

$$G_\varphi = -0.0000015\varphi + 0.9877.$$

Yeo et al. (2015) derived SD gain prediction model from experimental inference in Yeo et al. (2011) which concluded that the SD gain depends only on three factors; single site attenuation, A_s site separation distance, d and elevation angle, θ. The model was in different structure than Hodge's model such that in (4) (Yeo et al. 2015). The authors' new model was compared with ITU-R Hodge-based model (empirical model) and ITU-R Paraboni–Barbaliscia (P–B) model (physical model). The result was in favor of Yeo's model which was based on 2025 slant path attenuation of 10–30 GHz frequencies at 45 sites in Singapore with elevation angle ranged from 10° to 90° at intervals of 20°. The site separation distance was varied from 5 to 37 km.

$$G_{SD} = \left(-0.78 + 0.88A_s\right)\left(1 - e^{-0.18d}\right)\left(1 + e^{-0.14\theta}\right). \tag{4}$$

Methods

A live measurement to monitor the SD scheme has been conducted at gateway stations, Cyberjaya (101.6584° E, 2.9356° N) and Rawang (101°33′16.6″ E, 3°18′13.1″ N) separated by a direct distance of 42.52 km. This monitoring activities are currently running by MEASAT Satellite System Sdn. Bhd., at Ka-band frequency (20.2 GHz) using large diameter earth station antenna of 7.3-m with antenna gain of 62.31 dB, elevation angle of 68.8° and vertical polarization. The antenna received signals from MEASAT-5, a high throughput satellite (HTS), with 87 Ku-band and 10 Ka-band transponders, deployed by space Systems/Loral (SS/L) contractors, located at 119.5° E with 63dBW EIRP. The beacon receiver samples in time series with 2 s interval at Cyberjaya and 1 s interval at Rawang, stored in daily basis. The slant path attenuation at both locations was obtained by averaging each data to 1-min, thus deducting it with the clear sky value of the day. The spikes and outliers that were found in the time series data were eliminated, and 2 days (four files with the same date at Cyberjaya and Rawang) that consisted of data anomalies were removed as well. The anomalies might be caused by system malfunction or system under maintenance as they appeared to begin at the same point of time, such that in Fig. 1. Cyberjaya showed longer period of data unavailability in Fig. 1. The percentage of data availability in average was 95.13% at Cyberjaya and 95.4% at Rawang for four years of measurements from January 1st, 2014 to December 31st, 2017. Further analyses and single site results could be viewed in Samat and Mandeep (2020).

The averaged 1-min CCDF attenuation graphs were to allow the determination of joint attenuation. An internal program was developed to screen the data to get the lowest attenuations amongst two sites. The program compares every 1-min average data for each day in Cyberjaya with the same data and day in Rawang. Two rain gauge was located near the stations, to record the rainfall in 1 min. The rain gauge was installed by Department of Drainage and Irrigation (DID) Selangor, Malaysia to monitor the rain pattern at Cyberjaya and Rawang area, from January 1st, 2014 to December 31st, 2017. Rain value in millimeter (mm) was converted to millimeter per hour (mm/h) to represent the rain rate by multiplying each with 60. The 1-min rainfall was arranged in ascending order to calculate the frequencies of the same rain rate. Then, the probability of occurrences was derived using the accumulated frequencies divided by total amount of minutes for 1 month, thus the rain rate at percentage of probability of interest could be determined.

Baseline orientation angle was determined by measuring the angle between azimuth line and baseline distance of Cyberjaya and Rawang, as shown in Fig. 2. The baseline orientation angle was carefully ascertained based on the guideline given in the literature (Hodge 1981; Ippolito 2017; Panagopoulos et al. 2005). Therefore, the significant parameters involved in this measurement are as listed in Table 1. From Table 1, the parameter associated with the SD prediction model was taken as input. Each SD gain prediction model was reconstructed using Microsoft EXCELL including ITU-R P.618–13 diversity gain model. The average of 4 years measurement slant path attenuation at both sites was determined and was taken as input to the model as well. All results were discussed in the next section.

Results and discussions

From the experiment, the attenuation values were plotted and the percentage of time exceedance at 1%, 0.1% and 0.01% were observed. Figures 3 and 4 shows the average monthly attenuation graph at Rawang and Cyberjaya for 4 years started from 1st January of 2014 to 31st December of 2017. From Fig. 3, the highest average of attenuation was observed in April and November in Rawang. November is within northeast monsoon which started from November to March, and inter-monsoon is between end of March to end of April, then May to September is the southwest monsoon in Malaysia's weather (Omotosho et al. 2017). The month of February experienced the lowest attenuation among all the months in the 4 years. From Fig. 3, the average attenuation for percentage of signal unavailability at 1% of time was around 3 dB, 0.1% was in between 4 and 8 dB and 0.01% was around 10–30 dB, then the twelve's graphs tend to saturate above the 30 dB value. This might be due to the limitation of dynamic range value of the beacon receiver. At the same time, this beacon also received high noise from the

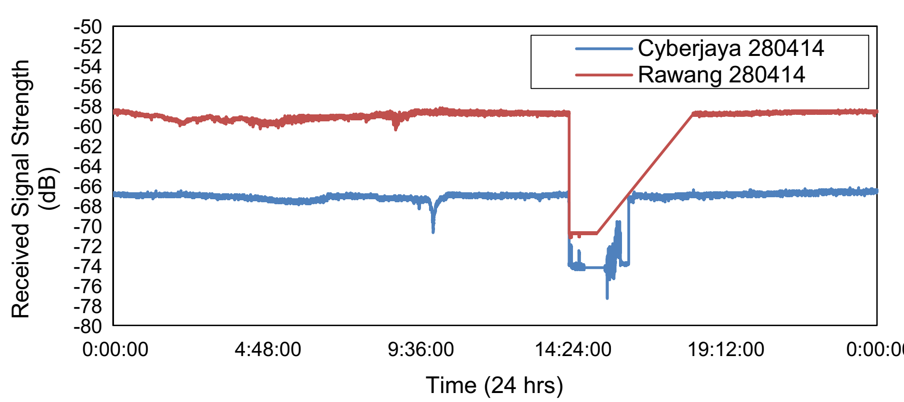

Fig. 1 Data anomalies on 28th of April 2014 during the same period at Cyberjaya and Rawang.

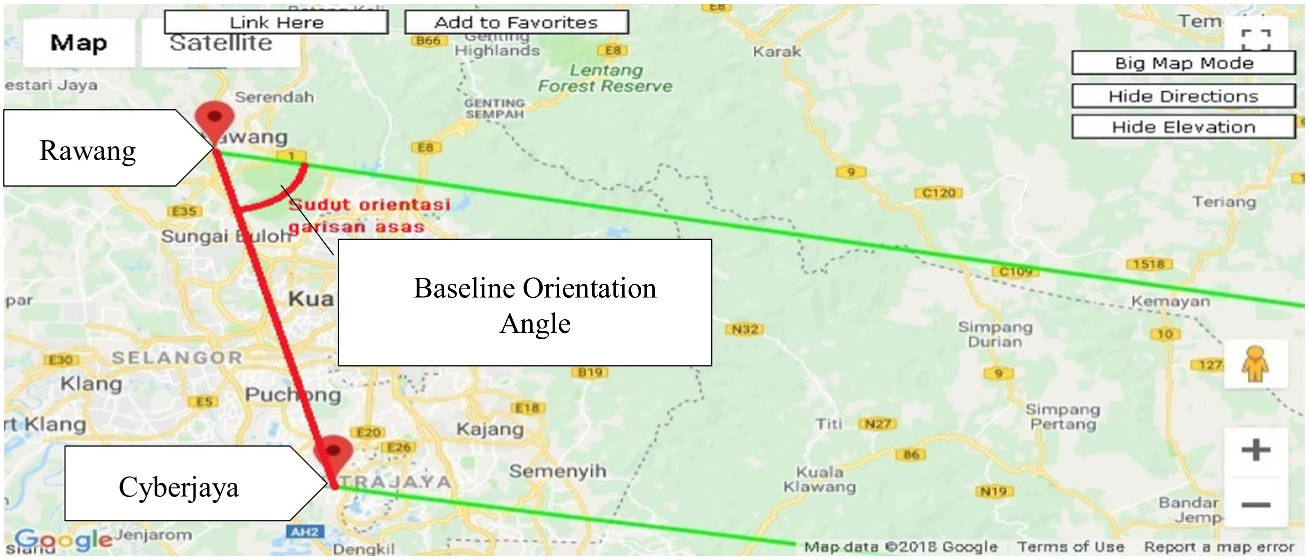

Fig. 2 Baseline orientation angle, an angle between azimuth line (green line) and baseline direct distance of Cyberjaya and Rawang

Table 1 Parameter for SD gain measurement

Parameter	Cyberjaya	Rawang
Frequency (GHz)	20.2	20.2
Azimuth angle	99.3°	100.4°
Altitude (km)	0.01962	0.038
Elevation angle (°)	68.8°	68.8°
Antenna diameter (m)	8.1	8.1
Polarization	Vertical	Vertical
Baseline orientation angle	65°	65°

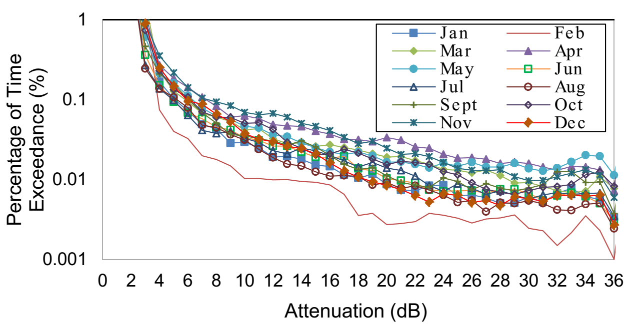

Fig. 3 Average monthly attenuation from year 2014 to 2017 in Rawang

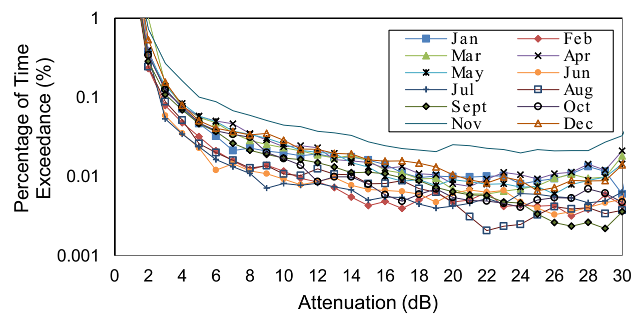

Fig. 4 Average monthly attenuation from year 2014 to 2017 in Cyberjaya

system as well as airspace causing it to mistakenly identify the noise as a signal from the satellite.

The graph of attenuation in Cyberjaya from 2014 to 2017 in Fig. 4 depicted that the attenuation range of over the time of 1% was 1.5–2 dB, 0.1% was 2.6–5 dB and at 0.01% was from 8.2 to 24 dB, then the graph saturated and flat at around 26–27 dB. From this whole graph, it is observed that November was experiencing greater attenuation over the other months, as seen from the state of the graph being separated between the other graphs. The least attenuation was experienced in July when considering at 0.01% of signal outage time. Afterall, the attenuation value experienced in Cyberjaya at all months was less than Rawang. This condition is seen in relation to Fig. 6 which shows the low average rain intensity at 0.01 percentage of time exceedance of that site for 4 years compared to Rawang as in Fig. 5.

From Fig. 5, the rain rate was high in November at Rawang and the least was in February, the same goes at Cyberjaya in Fig. 6. The value of this monthly average accumulation is consistent due to northeast monsoon which is occurred in November to March of every year. The average of rain rate at 0.01 percent of time at Rawang ranges from 45 to 116 mm/h, and Cyberjaya ranges from 39 to 112 mm/h. The average rain intensity for each year

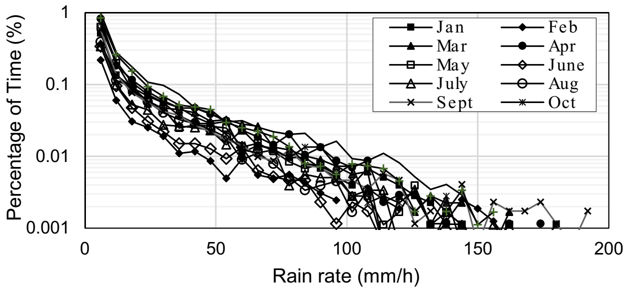

Fig. 5 Average (2014–2017) rain rate of each months at Rawang

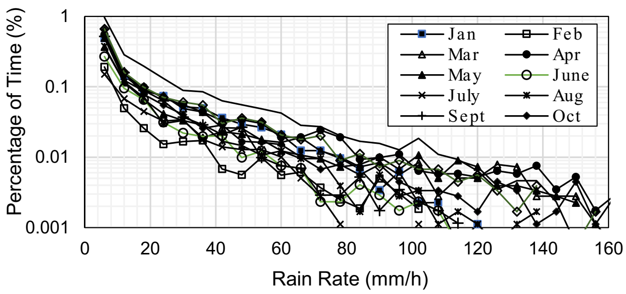

Fig. 6 Average (2014–2017) rain rate of each months at Cyberjaya

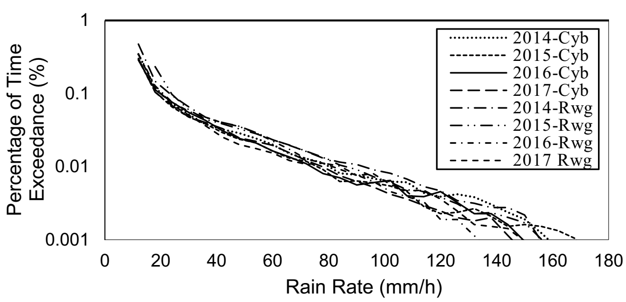

Fig. 7 Average rain intensity from year of 2014 to 2017 at Cyberjaya (Cyb) and Rawang (Rwg)

is displayed in Fig. 7. The rain intensity of 0.01 percentage of time exceedance at Cyberjaya was 80 mm/h, 76 mm/h, 74 mm/h and 78 mm/h in year of 2014, 2015, 2016 and 2017, respectively. While at Rawang, rainfall was more intense than Cyberjaya such that 92 mm/h, 82 mm/h, 84 mm/h and 81 mm/h in year 2014, 2015, 2016 and 2017, respectively, at the same percentage of time. Even though statistics conducted by Shayea et al. (2018) presented the average of 120 mm/h, the collected data were from June 2011 to May 2012. The author also admitted that the ITU-R latest prediction rain rate for Malaysia is still under investigation. Nevertheless, the latest ITU-R P.837–7 stated that the rain intensity in Malaysia is about

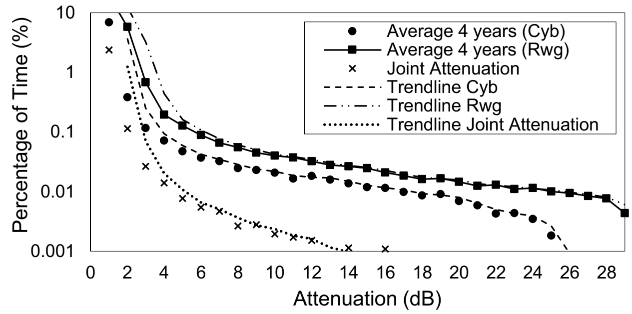

Fig. 8 Average 4 years measurement of attenuation CCDF at Cyberjaya and Rawang and their joint attenuation.

100 mm/h. Therefore, in this case, the measurement of rain data did not differ much than predicted by ITU-R.

The average of attenuation and joint attenuation of year 2014–2017 at each site was deduced and compared. Figure 8 depicted that the trendline (average of two period) attenuation at Rawang for 4 years measurement was 25.8 dB and at Cyberjaya was 17.4 dB. The differences between joint attenuation and single site attenuation at the same percentage of time were noted as gain. The site diversity improvement factor (IF) is calculated by taking the ratio of percentage of time of the same attenuation point at both sites, such that in (5). P_s is the percentage of time exceedance of single site (main sites), whereas P_d is the percentage of time exceedance of the joint graph at the same attenuation value. In this case, taking 12 dB of attenuation in Fig. 8 correlates to 0.02% of time exceedance at the Cyberjaya site and about 0.0016% of time exceedance at the diversity graph. Therefore, at this point of attenuation, the IF was 12.5, which mean a great improvement. This leads to meaning that for the same attenuation threshold, the signal unavailability could be improved to 0.0016% of time of an average year using site diversity scheme instead of only 0.02%.

$$\mathrm{IF} = \frac{P_s(A)}{P_d(A)}. \tag{5}$$

From Fig. 8, it was measured that the gain obtained at 0.01 percentage of time was 12.2 dB, measured between joint attenuation and Cyberjaya (main) site. The induced gain was compared with site diversity gain models as in Fig. 9.

All site diversity gain models deviated far from the measured gain at 0.1 percentage of time, as shown in Fig. 9. When percentage of time exceedance was approaching 0.02%, the Hodge model predicted gain was similar with the measured gain, then it goes a bit underestimated the gain at 0.01% of time. At this point of percentage of time, Semire model apparently predicted the closest value as the measured gain. Following through the decreasing of time percentage, it can be

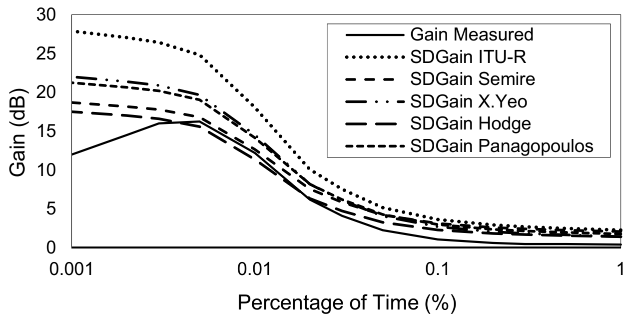

Fig. 9 Comparison of each model; ITU-R, Semire, X.Yeo, Hodge and Panagopoulos with the measured gain

Table 2 RMSE value of each model

Models	RMSE
ITU-R	0.578725742
Semire	0.507469426
X.Yeo	0.425821738
Hodge	0.383566864
Panagopoulos	0.476878661

noted that the measured gain was saturated at 0.005% of the time as what can be observed from the source of the original attenuation. Up to this point of percentage of time that the gain saturated, Semire model seems to have equal consistency of predicted gain value to the measured data. To further analyze the performance of each model, a statistical evaluation was performed according to ITU-R P.311–13 (2009). The root mean square error (r.m.s.e) was identified using formula (7). The test variable T_i was obtained from the logarithm of the ratio of predicted gain, G_p and measured gain, G_m, formulation of (6). For the measured gain less than 10 dB, a scaling factor is applied and without scaling factor for gain value of greater than 10 dB. The r.m.s.e values, denoted as *rmse*, was derived from the calculated mean, μ_T and its deviation, σ_T for each percentage of time. While N is the number of test variables and i is the count variable up to N. Table 2 shows the r.m.s.e values of each models.

$$S_i = \frac{G_{pi}}{G_{mi}}, \tag{6}$$

$$T_i = \left\{ \begin{array}{c} \left(\frac{G_{mi}}{10}\right)^{0.2} x\ln\left(S_i\right) \text{for} G_{mi} < 10\text{dB} \\ \ln(S_i) \text{for} G_{mi} \geq 10\text{dB} \end{array} \right\}, \tag{7}$$

$$\mu_T = \frac{1}{N}\sum\nolimits_{i=1}^{N} T_i, \tag{8}$$

$$\sigma_T = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(T_i - \mu_T\right)^2}, \tag{9}$$

$$\text{Withrmse} = \sqrt{\mu_T{}^2 + \sigma_T{}^2}. \tag{10}$$

From the results of r.m.s.e, it is found that the Hodge model predicted the smallest error as a whole, calculated from a time exceedance of 1–0.005%, that is, before the time the measured graph gain changes to fall down. However, Hodge model tends to underestimate the gain from 0.005% and downward if the measured graph were to be extrapolated up to 0.001% of time. It was obvious that the second least error was X. Yeo model, followed by Panagopoulos, Semire and ITU-R model. From the analysis of the models' shape, X. Yeo and Panagopoulos model were portrayed similar shape with the measurement graph, which shows abrupt negative slope as the percentage of time decreases, at point 0.02% of time and downward. However, the gain predicted by both models is higher than the measured one, as if the measured gain was positively shifted at y-axis at a certain scale. X. Yeo model seems the most suitable prediction model for this sample data, since it predicted less error than Panagopoulos model, and another merit is that it is having the same shape pattern of graph with the measured data. While Semire model apparently has the least error from 0.02% of time up to 0.005% of time, the model predicted bigger error from 1 to 0.02% of time percentage. This contributes to larger r.m.s.e to Semire model's prediction.

Conclusion

The measurement of this study was obtained from two sites of Malaysia, at Cyberjaya and Rawang, of Ka-band HTS signal with large diameter of antenna and high elevation angle. The gain at 0.01% of time was measured as 12.2 dB, and when comparing with other models, at the same percentage of time, Semire Model shows the most suitable for the measured data. However, in overall, from the percentage of time exceedance of 1% up to 0.005%, where the point of attenuation saturated, none of models shows a comprehensive match to the measured gain. Though Hodge model shows the least r.m.s.e., yet from the visual observation of the graph, the lowest r.m.s.e value does not mean that it successfully predicted equal value as the measured gain for the whole percentage of time exceedance, only it portrayed less error than other models. The closest pattern of models' graph with the measured one was X. Yeo and Panagopoulos models, but both models overpredicted the gain. More research should be explored to further digging the characteristics and factors that contribute to the development of site diversity gain model especially that is related to the pattern differences of two site's attenuation thresholds, which are mainly influenced by the intensity of the local rain. Therefore, from the observation of the analysis, the gain contribution to develop a prediction model such as frequency, baseline angle, elevation angle and separation distance should be analysed further.

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Compliance with ethical standards

Conflict of interests On behalf of all authors, the corresponding author states that there is no conflict of interest.

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