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A Comprehensive Review of the Site Diversity Technique in Tropical Region: Evaluation of Prediction Models Using Site Diversity Gain of Greece and India

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ABSTRACT The satellite signal deteriorates as it propagates from the source to the ground antenna on the surface of the earth. While some losses involving the amplitude and energy of the signal are unavoidably recovered due to the long slant path through the atmosphere, the impairment due to precipitation, especially rain, can be mitigated. Site diversity is one of the ways to obtain a less rain-attenuated signal, simply by preparing the other site to receive a link similar to that of the main site. Dual site diversity is common in practice with a site separation distance of at least a rain cell extent. This article presents an overview of the site diversity concept and a description of all parameters involved regarding the factor that contributed to the gain, which has been used as a performance metric to measure the effectiveness of a site diversity scheme. A detailed assessment of the capability of the gain prediction model is presented using site diversity experimental data conducted in two different climatic groups, namely, Greece in a temperate region and India in a tropical climatic region. The models involved in the evaluation were the ITU-R, Hodge, and Panagopoulos models, which were validated using temperate regional data, and the Semire and Yeo models, which were validated using tropical regional data. The observations of model behavior revealed that the Semire and Yeo models of the tropics were consistent with the measured gain obtained from India and Greece, respectively; thus, this demonstrated that the direction of future prediction models should consider both climates in the validation process.

INDEX TERMS Signal degradation, model evaluation, tropical region, rain-induced attenuation, atmospheric effect.

I. INTRODUCTION

Wireless networks have begun to be necessities for populations in recent decades. The capacity and capability of the network are growing to meet the demand of consumers with the emerging trend of handheld devices. Satellite broadband networks are needed more in areas that cannot be reached by terrestrial networks, especially in areas with remote geography, covered with foliage and hilly or vast sandy areas. Satellite signals function more during disasters, for military purposes, weather monitoring, broadcasting, and for many other uses related to industries [1]. While the focus of multibillionaire company profit-makers, accommodating more bandwidth to services is a challenge. Although Ku-band frequency signals are effortless, Ka-band and above frequencies are the aims of every satellite technology provider because of their capabilities in delivering more data bandwidth to consumers [2].

Although the benefits of higher frequencies are pronounced, satellite signals propagate in Ka-Band and above frequencies suffer a deterioration in magnitudes and powers [3] when entering the Earth's atmospheric layers, especially in the troposphere layer, where precipitation occurs [4], [5]. Rain is the major impairment for the signal carrying the high frequency, causing it to be exacerbated

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more, and in some conditions, it could be lost during the travel to the antenna receiver [6], [7]. The rain induced-attenuation becomes more severe during heavy rain, which is more common in the tropical region than in the temperate region [8]. Some mitigation techniques, such as power control and adaptive waveforms, are not effective because they induce interference, and in some conditions, there is a need to request permission from consumers to possibly reduce the bit rate [9]–[11], which can cause further delay, compromised data quality, misleading content, and user dissatisfaction, especially in broadcasting industries or during the transmission of vital messages in the case of disasters. Therefore, one way to overcome this is to use diversity techniques, which include satellite diversity, frequency diversity, time diversity, and site diversity. The site diversity is more effective and practical to be applied in a region that has the potential to experience very high rain-induced attenuation, namely in tropical climates. Moreover, the site diversity technique can also be applied simultaneously in conjunction with other diversity techniques [12], [13].

The site diversity gain prediction models are used to predict the effectiveness of a site diversity scheme (SDS) in terms of the achieved gain called site diversity gain (SDG). These models are designed to facilitate the deployment of the site diversity concept; therefore, they remain to be tested for accuracy and reliability. The models are a multiplication of several parameters that contributed to the total predicted gain. Nevertheless, there are different views regarding these contributor parameters, which differ by region.

The objective of this paper is to provide a comprehensive view of the site diversity concept and to reveal multiple past site diversity experiments conducted in tropical regions. Those experiments' discussions are concerning the effects of four parameters that contribute to the value of the SDG, which include the site separation distance, link frequency, antenna elevation angle, and baseline orientation angle. These parameters are essential to determine the behavior of an SDG prediction model. The examples of existing models are presented in this article to explicitly investigate their behavior.

The flow of this article is as follows. The site diversity concept and the metric to evaluate the effectiveness of the performance of an SDS are explained in section 2. The evolution of a prediction model started in the temperate region, and then the prediction model emerged in the tropical region from a series of site diversity experiments. These are described in section 3. Furthermore, each site diversity experiment deduced results that correlated with the four parameters; therefore, they are also presented in this section. Section 4 discusses the evaluation of each prediction model, namely, the Hodge, ITU-R, Panagopoulos, Semire, and Yeo models, using two different SDGs that were extracted in temperate regions and tropical climate regions, namely, Greece and India. The results of the evaluation analysis and the basic errors are calculated. Finally, conclusions are drawn in the last section.

II. SITE DIVERSITY IN THE LITERATURE

Site diversity is a technique that takes advantage of the inhomogeneity of rainfall in tropical regions. Rainfall is categorized into three types: convective, stratiform, and stormwind [14]. Convective rain is a heavy rainfall that lasts for a short period of time within a limited distance. Stratiform rain is a gentle rain-like drizzle that lasts longer and normally occurs over a longer distance. Storm-wind rain is rain that occurs with intense dark-grayed clouds and sometimes with hurricanes and typhoons, which occur with moderate durations and short distances but with disastrous effects. Since the types of rain are related to distance, which is called rain cell, then a station that receives a satellite signal in one place will experience different rain attenuation with another station that is beyond the distance of a rain cell that receives a similar signal from the same satellite [15].

Thus, site diversity is a concept that uses two satellite signal receiver stations simultaneously, with one station as the primary station, and the other station as the diverse station. The stations are separated by a minimum distance of rain cells so that each one receives a different type of rain, indirectly, the signal received by each station experiences different rainfall attenuation as well. Thus, the signal from any site that has the lowest attenuation would be routed to the primary station for communication system purposes [16].

The site diversity setup fundamentally seems to be an observation of trial and error in practice. This is because the second site to be chosen as the diverse station should have a different pattern of rainfall than the reference station. Therefore, investigations on the second or diverse site effectiveness or performances are determined using two metrics: site diversity gain (SDG) and improvement factor (IF) [17].

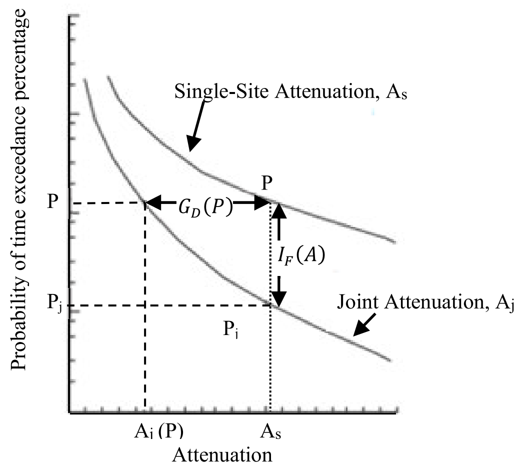

FIGURE 1. The correlation of SDG, which is denoted as G_D, and IF, which is denoted as I_F with single-site attenuation, A_S and joint attenuation, A_j and the probability of time exceedance, P.

Figure 1 illustrates the definitions of SDG and IF, denoted as G_D and I_F respectively, and their correlation with the single-site attenuation and the joint attenuation. The collective SDG values are the differences between the least attenuation between two sites; the joint attenuation, A_j, and the single-site attenuation, A_s, which is normally the attenuation at the primary site.

From Figure 1, the instantaneous value of the SDG, which is denoted as $G_D(P)$, is determined by taking the difference of A_j at the probability of time P, denoted as $A_j(P)$, and the single-site value A_s at the same probability of time, $A_s(P)$. The instantaneous value of the IF, denoted as $I_F(A)$, is determined by taking the ratio of the probability of time of the same value of attenuation at the graph of single-site attenuation, P (A_s), and the graph of joint attenuation, P_j (A_s). The formulas for obtaining the instantaneous values of SDG and IF are given in (1) to (3), wherein A_D is the attenuation value of the diverse site.

$$G_D(P) = A_s(P) - A_j(P) \quad (1)$$

$$A_j(P) = \min(A_s(P), A_D(P)) \quad (2)$$

$$I_F(A) = \frac{P(A_s)}{P_j(A_s)} \quad (3)$$

Although both metrics are essential for measuring the effectiveness of an SDS, the SDG metric is widely used because the IF has weaknesses due to its calculation, which uses the percentage of probability of time. One flaw is that the ratio at the very deep fade could not be measured because the graph of joint attenuation normally will go extremely low in percentage; therefore, the ratio could become undefined. Another reason is that because of the duration limitations of an experiment, the calculation might induce uncertain results [18]. Thus, the IF is seen as more prone to statistical errors because it is evaluated from samples of different sizes, particularly at large attenuation [19]. Therefore, we referenced the rest of this article's discussions on the SDG.

The deployment of the second sites for an SDS consumes costly preparation, which includes redundancy in pieces of equipment and terrestrial underground cable infrastructure to provide a reliable connection between two stations. Therefore, it is a relief if the expected second site effectiveness could be measured beforehand. An SDG prediction model seems to be a reasonable way to provide this information before implementing any site diversity scheme. Thus, Hodge proposed an empirical SDG prediction model published in his article in 1976 and refined in 1981 [20]. The model incorporates four factors that contribute to the SDG value namely site separation distance, link frequency, antenna elevation angle, and baseline orientation angle. The model is the product of gain multiplication for each of the SDG contributing factors, i.e. site separation distance gain, G_d, frequency gain, G_f, the gain of antenna elevation angle, G_θ, and the gain of baseline orientation angle relative to the propagation path, G_φ. The general formula is as presented in (4), where G_D represents the SDG [21].

$$G_D = G_d G_f G_\theta G_\varphi \quad (4)$$

Figure 2 demonstrates those four factors that contribute to the value of SDG, as defined by Hodge Model. In recent years, an investigation regarding the gain contributing factors to the SDG prediction model has been performed to determine the correlation of gains according to the local climate. High SDG values contribute to the possible chances of the expected site being chosen as a diverse site in an SDS. Site diversity experiments come from inhomogeneous data sources, such as direct data measurements from satellite signals and rain rate data that are extracted from radar or rain gauges, consequently converting the data to rain attenuation data using rain attenuation prediction models such as ITU-R P.618, the synthetic storm technique (SST) or the personalized authors' formula. The SDG values are then determined based on the attenuation results from the experiments to the extent of comparing the SDG prediction models and thus giving birth to the emergence of multiple models depending on those correlation factors that are based on the local measurements or the database of SD experiments maintained by the ITU-R Study Group 3 (DBSG3) [22].

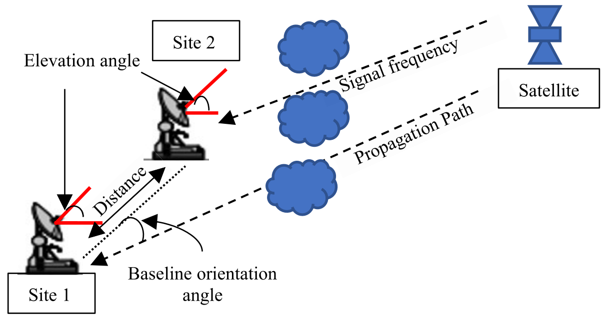

FIGURE 2. Four factors that contribute to the SDG are the site separation distance, signal frequency, elevation angle of the receiving antenna, and baseline orientation angle.

III. SDG INVESTIGATIONS AND PREDICTION MODELS

The SDG prediction models are categorized into two types of models, empirical and physical-mathematical models. The first estimates the SDG from the correlation of four factors that contribute to the gain in terms of analytical functions as a result of regression analysis on the SDS experimental data. The latter predicts the joint cumulative distribution or joint probability of rain attenuation at the receiving sites to estimate the outage probability. There are a few physical-mathematical models available, such as those proposed by Bosisio and Riva [19] that represent the rain area by synthetic rain cells, namely, EXCELL (EXponential CELL), to produce rain attenuation from the span of a maximum of 20 km, which was later expanded by Luini and Capsoni [22] to 250 km of site separation distance. Kourogiorgas *et al.* [23] used an inverse Gaussian (IG) distribution, while Das and Jameson [24] used raindrop size and thus the Bayesian inverse technique to generate the spatial rain field for consequent rain attenuation. Kelmendi *et al.* [25] used a Gaussian copula to model the joint exceedance probability for dual-site diversity. All those techniques that use the physical input produce a graph similar to Figure 1 and the values from the figure are used to calculate the SDG values using (1). ITU-R P.618-13 [26] adopted the physical model of Luglio *et al.* [24], [27] in its documented guideline under section 2.2.4.1. Since the physical entity used for the input of these models is hard to prepare, this article focuses on the empirical model because it produces faster results due to easily obtainable data, and uses more understandable assumptions than the physical-mathematical model.

The empirical model initiated by Hodge is adopted in ITU-R P.618-13 in section 2.2.4.2, with a few modifications on the model's coefficients to suit ITU-R's databases. The ITU-R prediction model and the Hodge prediction model are suitable for predicting SDG values at SDS sites less than 20 km from each other. Bosisio *et al.* [28] compared the Hodge model with other empirical models, created by Allnutt and Rogers, Goldhirsh, and International Radio Consultative Committee (CCIR – now ITU-R) and with the physical-mathematical model proposed by Mass, Matricciani, and Capsoni using 47 site diversity experiments data investigated in temperate regions. Those experiments used frequencies ranging from 11 GHz to 30 GHz and site separation distances ranging from 2 km to 37.5 km. The results of the model evaluations showed that the model proposed by Hodge gives the best prediction compared with the other models. However, from the observations of the 47 listed site diversity experiments used, 24 experiments employed site separation distances in between 10 km to 20 km which is 51% out of the whole data. Meanwhile, 8 experiments used less than 10 km and 15 experiments used greater than 20 km wherein each contributed to 17% and 32%, respectively from the total site diversity experiments used for the validation. The data used for the model's comparison consists of more SDS experiments that used site separation distances less than 20 km, which represents 68% of the total data. Therefore, the validation results of these models are undoubtedly in favor of the Hodge model. Thus, although the Allnutt and Roger model is tailored for the site separation distances greater than 20 km, because the data validation range used suits the Hodge model more, the Allnutt and Roger model are observed to show worse performance.

Panagopoulos *et al*. [29] defined a short site separation distance as below 15 km, and greater attenuation decorrelation could be experienced at site separation distances longer than 15 km. The author investigated Hodge's model and claimed that the influence of the site separation distance on the SDG deduced by the respective model is exceedingly small and almost negligible for distances greater than 10 km. The author proposed a new model in line with Hodge's model with the attenuation gain, G_A, as a new element to be multiplied by the other gains. Thus, from the sensitivity analysis performed by the author, Panagopoulos's model appears to be more sensitive to the variations of distance than Hodge's model. The models were tested on 41 site diversity experiments of site separation distances below 15 km, and 35 experiments of greater than 15 km that were conducted in temperate regions. From the observations of the listed experimental data, 29 experiments used a separation distance of less than 10 km, 32 experiments used a separation distance between 10 km and 20 km, and 15 experiments used a separation distance greater than 20 km. Each data range represents 38%, 42%, and 20% of the total 76 experiments, respectively, showing that the experiment with the range below 20 km distance is 80%, which represents the majority.

Nagaraja and Otung [30] proposed a new model based on radar measurements to predict the SDGs at frequencies between 16 GHz and 50 GHz, which the authors indicated are not covered by previously mentioned models. The model is produced with different coefficient values according to the distance ranges; namely, 4 km to below 14 km and 14 km to 38 km, and elevation angles from 10° to 50°. The author compared the proposed model with the model of Panagopoulos, the ITU-R SDG prediction model of section 2.2.4.2, and the ITU-R physical-mathematical model of section 2.2.4.1. The limitations of the model proposed by Nagaraja and Otung are seen in the elevation angle and site separation distance, in which it is more appropriate to use up to 50° and 38 km, respectively.

While the abovementioned models are exclusively designed and validated using experimental data in temperate regions, an examination of the most affected areas, such as tropical regions, is necessary. Site diversity investigations in tropical regions were reported in 2001 by Timothy *et al.* [31], who discussed a preliminary study on the SDS in Singapore using two sites receiving 11.198 GHz signals from the INTELSAT satellite. The primary site was at Nanyang University, and the diverse site was at Bukit Timah, both separated by 12.3 km. The elevation angle used was 42.8° with a baseline orientation angle of 4°. The authors compared the SDG deduced from the scheme with the Hodge and ITU-R models. The outcome concluded that both models suit the measured SDG.

In 2008, Pan *et al.* [32] reported an SDS conducted in Lae, Papua New Guinea using 12.75 GHz signal data from satellite OPTUS-B at 160°E, measured from June 1994 to May 1995. The reference site was at Lae University with a rain accumulation of 4972 mm, and the diverse site was at the Lae Post Office with 6500 mm yearly rain accumulation, with both sites separated by 6.5 km. The authors reported that the outcome attenuations at both sites differed considerably, although the site separation distance did not differ greatly. This might have been caused by the differences in geographic terrain at each site, with the observation that the convective rain at one site transforms to stratiform rain at another site in a period of no time.

In their article of the year 2010, Shukla *et al.* [33] introduced a microcell site diversity concept conducted in Ahmedabad, India, using a 30 GHz signal frequency and elevation angle of 61°. The authors placed seven rain gauges at multiple separation distances from 180 m to nearly 900 m to perform a similar SDS as they believed that the rain cell in India in the tropics was shorter than that in temperate regions. The data were measured from 2007 to 2008. Each SDG was deduced from the conversion of rain rate to rain attenuation using the ITU-R rain attenuation prediction model. Hence, these SDGs were compared with those from the ITU-R SDG prediction model. From the observations of the attempts, the authors concluded that the ITU-R model delivered the same SDG values although the site separation distance was set farther; thus, the model did not consider the various distances in the microcell. Bijoy *et al.* [34] used two years of data and converted the rain rate using SST, and the baseline orientation angle was set to 90°. They observed that at an extent of 496 m, the SDGs reached a maximum but then decreased as the site separation distance increased more than 496 m. Hence, they concluded that a new site was suitable to be placed approximately at 500 m to obtain the optimum SDG. Therefore, it was understood from the authors' experiments that the convective rain cell in Ahmedabad, India, was approximately 500 m far in radius to obtain inhomogeneous attenuation.

Yeo *et al.* [35] investigated rain cells in Singapore and concluded that the extent was up to 15 km. They mentioned in their article that wind direction might have contributed to the SDG. Nonetheless, they clarified the statement later that the wind direction was dependable and limited to the Singapore terrain. The rapid wind movement that brings rain from one place to another could cause the attenuation experienced at an SDS separated by a short distance to resemble each other [36]. The observation of wind movement by Yeo *et al*. appeared to be similar to the conclusion drawn by Pan, Allnutt, and Tsui, but the geographic terrain of a locality differentiates the formation of rain types. Thus, an investigation on an SDS in Singapore was performed, involving Nanyang Technological University, Singapore (NTUS) as the primary site and a place located in the southeastern NTUS (SE) as the diverse site. The NTUS coordinates are at 1.3483° north and 103.6832° east, and the SE coordinates are at 1.3148° north and 103.8656° east. From the observation of the SDG values inferred from the SDS, Yeo *et al*. reported that the frequency and baseline orientation angle appeared to have less influence on the SDG in the tropical region; therefore, they proposed a new SDG prediction model that suited the hypothesis.

In Guam of the United States of America, the Ka-Band site diversity experiment was conducted by Acosta *et al.* using two antennas located at the Guam Remote Ground Terminal of Dededo with one at the northern terminal separated by 0.6 km from another one at the southern terminal [37]. From observations of the deduced joint attenuation, although the site separation was not that far, there were at least 4 dB improvements for 99.9% of the time. Site diversity investigations were also conducted in Nigeria involving four places, with the University of Uyo as the main site, separated by 21.1 km to 117.29 km in distance from each other. We measured the baseline angle for this quadruple SDS from the location of the University of Uyo and concluded that the angle ranges between 15° and 50° [38]. The rain attenuation was estimated using rainfall intensity at each site as input to the ITU-R rain attenuation prediction model. The rainfall intensity is the result of the conversion of rainfall accumulation using the Chebil and Rahman formula, and later the Moupfouma and Martins model.

Another site diversity investigation in Nigeria was conducted in Lagos, by Abayomi *et al*., which was reported in his article of the year 2017 [39]. The study used three sites, which stated that Ikeja was the prime site, and Marina and Ikorodu were separated from Ikeja by 16.69 km and 17.67 km, respectively. Rain rate data were obtained from the rain gauge at each site and converted to rain attenuation using the ITU-R P.618-12 model. Both investigations in Guam and Nigeria shared a mutual agreement that the site separation distance was the key factor that influences the SDG, which could be increased if the distance was larger. As reported in his article in 2017, D'Amico *et al.* [40] also investigated multiple-distance site diversity in Guayaquil, Ecuador, of the equatorial region. The rain attenuation was deduced from the rain rate time series using SST, and then the SDG was determined. From the observations of four places separated from each other from 4.1 km to 17 km, the authors concluded that the diverse site should be placed in a location with different rainfall accumulation from the prime site to obtain an increase in SDG.

In Malaysia, Semire *et al.* [41] investigated an SDS using Tropical Rainfall Measuring Mission-Precipitation Radar (TRMM-PR) data with the prime sites in four Southeast Asian countries, namely, the University of Science (USM), Malaysia, Bandung Institute of Technology, Indonesia (ITB), University of the South Pacific (UPS), Fiji and University of Ateneo de Manila (UAdM), Philippines. For each main site, there were five diverse sites at various locations and separated by 2.35 km to 51.09 km from their main site. From the observed SDGs of the multiple SDSs, the authors concluded that the SDG depended on the site separation distance and elevation angle and was less influenced by the signal frequency and baseline orientation angle. Based on the hypothesis, the author proposed a new SDG prediction model that is in line with the structure of Hodge's model. The model is derived from the rain rate and rain attenuation of these multiple SDSs in the four Southeast Asian countries. Although the conclusions are similar to those of Yeo *et al*., Semire *et al*. still included the frequency and baseline angle as factors that contribute to the overall multiplication in the formula, whereas the Yeo formula does not include those factors [42]. All parameters could be retrieved from the cited article.

Another report of an SDS investigation was from Rafiqul *et al.* [43] using rain rates at four sites that were separated by 6 km to 37 km in Selangor, Malaysia. The SDG acquired from the SDS appeared to have no increase after the site separation distance reached beyond the rain cell of approximately 30 km [44]. This conclusion differs from that of Shukla *et al*., who discovered an increase in the SDG to a certain extent of a rain cell and differs from Yeos', who estimated that the rain cell in the tropics is approximately 15 km. In his later article, Rafiqul *et al.* [45] reported an estimated SDG at two sites involving the International Islamic University, Malaysia (UIAM) and National University of Malaysia (UKM), separated by 37.36 km. The rain attenuation was deduced from the rain rate measured by rain gauges at both sites. The rain data were acquired in 2015. The SDS was simulated using a 12 GHz frequency and 77.4° elevation

TABLE 1. Advantages and limitations of the empirical SDG prediction models.

Year	Model	Data Sources	Advantages	Limitations
1981	Hodge [18]	34 data measurement set from the temperate region (Canada, England, Japan, and United States of America)	• Pioneer model • Suits for an elevation angle of 30° • Suits for distances below 10 km [41]	• Inappropriate for elevation angles below 30° • Insensitive to distance diversity • Appropriate for separation distances below 20 km
2017	ITU-R P.618-13 [26]	Data were mostly from the temperate region and a few from the tropical region	• International Standard model • Widely used • Adopted from the Hodge model	• Assume rain attenuation is the lognormal process [22] • Appropriate for separation distances below 20 km
2005	Panagopoulos *et al.* [29]	Data from the temperate region	• Sensitive to the site separation distance • Taking into account the influence of attenuation depth on the gain	• Inappropriate for the data in the tropical region [41]
2012	Nagaraja and Otung [30]	• Data from the temperate region • Using radar measurements	• Cater frequencies between 16 GHz and 50 GHz • The formula varies according to distance	• Inappropriate for elevation angles above 50° • Limit up to distances below 38 km
2015	Yeo *et al.* [36]	2025 rain attenuation data were simulated from 45 various sites in Singapore using radar-derived rain rates	• Frequency and baseline angle has less influence on the gain • Simpler model	• Simulation is based on the geographic landscape of Singapore
2015	Semire *et al.* [42]	Rain attenuation data from four Southeast Asian countries (Fuji, Indonesia, Filipina, and Malaysia) using radar-derived rain rate	• Model structure in line with Hodge • Appropriate for ration distance from 1 km to 50 km	• Limited range of baseline angle • Inappropriate for elevation angles higher than 50°

antenna. The author then compared the measured SDG with the ITU-R, Hodge, Panagopoulos, and Semire prediction models at two baseline angles, which were 0° and 90°. From the two comparisons, it was found that the model proposed by Semire had deviated far from the measured SDG values, while the ITU-R and Hodge models could predict better than the Semire model, although both models were built based on data from temperate regions. This might have been because Semire designed his model based on elevation angles from 10° to 50° only and did not consider higher angles. The advantages and disadvantages of each empirical model are summarized in Table 1 for ease of reference.

Lam *et al.* [46] reported their research that was based on weather radar data from January 2007 to December 2008. The investigated SDS used the location of the radar at Sri Gading, Johor Bahru (SGJ) (2.02°N, 103.22°E) as the main site, and the diverse sites were selected at various locations ranging from 4 km to 56 km apart. The radar-derived rain rate maps were converted into attenuation maps using numerical integration, which can be found in [46]. The authors simulated the SDS using the assumption of 18.9 GHz frequency and 44° antenna elevation angle. The impact of the site separation distance on the SDGs was observed by plotting the SDGs according to the 4 dB step of attenuation. From the observations, the SDG value showed stability at approximately 20 km and beyond.

After all, from the investigation, the rain cell was concluded to differ according to the geographic landscape of the country and according to the locality. Jong *et al.* [47] started the campaign of the only Ka-Band investigations on an SDS reported that year in Malaysia using a 20.245 GHz signal frequency and elevation angles of 25.4° and 26.15° at the two sites, which were at the University of Technology, Malaysia (UTM) and Tun Hussein Onn University of Malaysia (UTHM), respectively. Jong reported that the attenuation measured at UTM reached 80 dB during a rain intensity of 135 mm/h at 0.01% outage time. Although the high attenuation may have been caused by many factors, in this case, it was due to the low elevation angle.

Table 2 lists the summarized parameters used by each site diversity investigation in the tropical region. There are a few SDS investigations that have not mentioned the baseline orientation angle in their respective articles; therefore, we measured these angles according to the given azimuth and the site's location. The highlighted parameters were mainly used to facilitate further investigations.

Table 3 summarizes the overall conclusion of the SDS study in the tropical region for ease of reference. Most studies have concluded that site separation distance has a major impact on the SDG values. Due to the inhomogeneity of rain, the attenuation at diverse sites located farther than the main site of at least a rain cell extent could increase the SDG value. Although Yeo *et al.* and Semire *et al.* suggested that frequency has less impact on SDG in the tropics, a comparison between an SDS using a similar frequency needs to be conducted to determine the influence of frequency on the SDG value with other parameters, such as elevation angle, site separation distance, and baseline angle, to be kept constant at all sites.

According to Ippolito [1], the baseline orientation angle will increase the SDG value if it approaches the value of 90°. The low elevation angle caused high attenuation due to possible rain events along the signal propagation direction; however, the angle could not be simply increased or decreased. The antenna receiver should be pointed to the intended satellite; thus, the adjustment of the antenna dish pointer is

TABLE 2. Summary of parameters used by past site diversity investigations in the tropical region.

Year	Site	Author	Frequency (GHz)	Distance (km)	Elevation Angle (Degree)	Baseline Angle (Degree)
2001	Singapore	Timothy, Ong, and Choo [31]	11.198	12.3	42.8°	4°
2008	Lae, Papua New Guinea	Pan, Allnutt, and Tsui [32]	12.75	6.5	72.8°	70°
2011	Ahmedabad, India	Bijoy, Shukla *et al.* [34]	30	0.18-0.9	61°	90°
2012	Guam of USA	Acosta *et al.* [37]	20.7	0.6	38°	83.5°
2015	Penang, Malaysia	Semire *et al.* [42]	12.255	12	40.1°	0°
	Johor, Malaysia	Lam *et al.* [46]	18.9	8	44°	0°
	Johor, Malaysia	Jong *et al.* [47]	20.245	70	25.6°	30°
	Singapore	Yeo, Lee, and Ong [36]	18.9	20.6	44.6°	12°
2016	South-South Nigeria	Jane *et al.* [38]	20	21.1-117.29	49°	15°-50°
2017	Lagos, Nigeria	Abayomi *et al.* [39]	12	16.69-22.70	44.5°	45°
	Guayaquil, Ecuador	D'Amico [40]	20	4.1-17	67.7°	<10°
	Selangor, Malaysia	Rafiqul *et al.* [45]	12	37.36	77.4°	81°

TABLE 3. A summary of the past site diversity experiments conducted in the tropics and their respective results.

Author	Site/Country	The results of the study	Model
Timothy, Ong, and Choo [31]	Singapore	▪ Baseline orientation angle 4°. ITU-R model suits the data.	
Pan, Allnutt, and Tsui [32]	Lae, Papua New Guinea	▪ High antenna elevation angle increases the G_D.	
Shukla *et al.* [33]	Ahmedabad, India	▪ Rain cell extent in India is short, only a few meters.	
Bijoy *et al.* [34]	Ahmedabad, India	▪ ITU-R model is insensitive to distance diversity.	
Yeo, Lee dan Ong [35]	Singapore	▪ Frequency and baseline orientation angle has less influence on the value of G_D.	
Acosta *et al.* [37]	Guam of USA	▪ Longer site separation distance could increase the G_D.	
Rafiqul *et al.* [43]	Selangor, Malaysia	▪ No increment of G_D beyond the rain cell extent of 30 km.	
Semire *et al.* [41]	Penang, Malaysia	▪ Frequency and baseline angle have little influence on the value of G_D.	
Semire *et al.* [42]	Penang, Malaysia	▪ Developed G_D a prediction model based on the rain attenuation data acquired from four Southeast Asian countries.	√
Lam *et al.* [46]	Johor, Malaysia	▪ No increment of G_D beyond the rain cell extent of 20 km.	
Jong *et al.* [47]	Johor, Malaysia	▪ Rain attenuation at Ka-band reached 80 dB due to the low antenna elevation angle (25.4°).	
Yeo, Lee, and Ong [36]	Singapore	▪ A developed prediction model based on 2025 slant path and rain attenuation data acquired from 45 sites in Singapore districts, represented in grid.	√
Jane *et al.* [38]	Selatan Nigeria	▪ Longer site separation distance could increase the G_D.	
Abayomi *et al.* [39]	Lagos, Nigeria	▪ G_D could be increased by extending the distance between sites.	
D'Amico [40]	Guayaquil, Ecuador	▪ The diverse site should be selected at the location with different rain accumulation from the main site to achieve high G_D.	
Rafiqul *et al.* [45]	Selangor, Malaysia	▪ The comparison of G_D prediction models, such that the ITU-R, Hodge, Panagopoulos, and Semire models showed that the ITU-R and Hodge models suited the data with high antenna elevation angle (77.4°).	

restricted to a limited range of angles; otherwise, there is a possibility of off-pointing the aimed satellite. Therefore, because the elevation angle is initially set by the experimenter and normally both sites are set to the same elevation angle, the impact of high and low angles to the SDG could be known by comparing the SDG of multiple SDSs with the other factors, such as frequency, site separation distance, and baseline angle are kept constant. However, those on-site comparisons involving frequencies and antenna elevation angle have yet to be found in the literature.

IV. PERFORMANCE EVALUATION OF SDG PREDICTION MODELS OVER MEASURED SDG IN GREECE AND INDIA

The SDG prediction models developed by the researchers mentioned before, namely, Hodge, ITU-R, Panagopoulos, Semire, and Yeo, were analyzed further in terms of their SDG dependency on the site separation distance. The full formulas of each model can be extracted in [48]. This article highlights the formula of each model that concerns site separation distance only. We do not include the model proposed by Nagaraja and Otung because there are some uncertainties in coefficients related to the distance to be applied. Each model is viewed at an attenuation value of 24 dB, and at site separation distance values of 0.6 km, 8 km, 12 km, 20.6 km, 42.52 km, and 70 km, which represent six of the SDSs available in the tropics, and can be found in Table 3 of [49].

Equations in (5) to (15) are the list of formulas that were extracted partly to show the behavior of each model towards the site separation distance. The Hodge model gain dependencies on separation distance are denoted as G_H, and the formula is from (5) to (7); the ITU-R model, G_{ITU}, is in (8) to (10); and the Panagopoulos model, denoted as G_P, is displayed in (11). The Semire and Yeo model gain dependencies on separation distance denoted as G_S and G_Y, are shown in (12) to (14) and (15), respectively. A is the single-site attenuation, and d is the distance. For each formula that requires the constants a and b, the respective values are displayed accordingly; for example, the constants a and b for

G_H are as in (6) and (7), respectively, while the a and b for G_{ITU} are as in (9) and (10), respectively. The same goes for the constant values of a and b of G_S, which are as in (13) and (14), respectively.

$$G_H = a(1-e^{-bd}) \quad (5)$$

$$a = 0.64A - 1.6(1 - e^{-0.11A}) \quad (6)$$

$$b = 0.585(1 - e^{-0.098A}) \quad (7)$$

$$G_{ITU} = a(1-e^{-bd}) \quad (8)$$

$$a = 0.78A - 1.94(1 - e^{-0.11A}) \quad (9)$$

$$b = 0.59(1 - e^{-0.1A}) \quad (10)$$

$$G_P = \ln(3.6101d) \quad (11)$$

$$G_S = a(1-e^{-bd}) \quad (12)$$

$$a = 0.7755A + 0.3374(1 + e^{-9.16A} \quad (13)$$

$$b = 0.1584(1 + e^{-0.03164A}) \quad (14)$$

$$G_Y = (-0.78 + 0.88A)(1 - e^{-0.18d}) \quad (15)$$

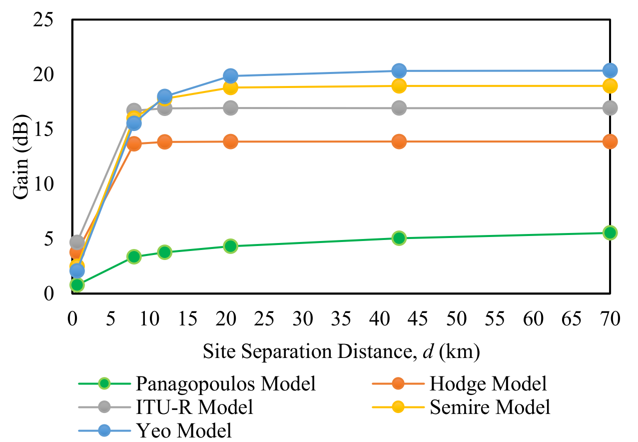

FIGURE 3. **The relationship of the predicted gain to the site separation distance of the Hodge, ITU-R, Panagopoulos, Semire, and Yeo models.**

Figure 3 shows the correlation of the predicted gain with the site separation distance of the Hodge, ITU-R, Panagopoulos, Semire, and Yeo prediction models. The Yeo model shows a rapid increase in gain at distances below 20 km. The increase in gain is seen to be slightly slower than before when passing 20 km up to approximately 40 km, and then the gain value is stable at a distance of more than 40 km. The predicted gain of the Semire model shows a similar trend with the Yeo model; only it predicted slightly higher values of gain from 0 km to 8 km, and then the model predicted lower gain than the Yeo model beyond a distance of 12 km.

The ITU-R model shows a rapid increase in predicted gain from 0 km to 8 km, and then the gain was predicted to have the same values afterward. The Hodge model behaved in a similar trend as the ITU-R model; only it predicted a slightly lower gain than the latter. The Panagopoulos model portrayed a different behavior than the rest. The model shows a rapid increase in the predicted gain from 0 km to 8 km. It was observed that there was a modest increase in gain from 8 km to 20 km, and after 20 km, the gain was increased as well but at a small rate compared to before. We observed that there is no saturated value of predicted gain in the Panagopoulos model graph, as shown by the other models.

These SDG prediction models were evaluated on measured SDGs obtained from two different climates available in the literature, which are Greece and India. Figure 4 shows the location of Greece and India on the world map.

FIGURE 4. **The world map displaying the location of Greece and India, shown in the red circles, along with the equatorial line.**

The SDS experiment investigated in Greece of the temperate region was conducted at the campus of National Technical University of Athens (NTUA) located at Zografou, and NTUA Lavrion Technological and Cultural Park (LTCP) at Lavrion, which were separated by 36.5 km [50]. The SDS in Greece, namely, NTUA-LTCP, used two identical beacon receivers residing at each of these sites. The beacons received and measured the power of ALPHASAT's Ka-Band continuous signal at 19.701 GHz in vertical polarization from the 1st of July 2016 to the 30th of June 2018. This SDS was chosen because the site separation distance was beyond 20 km.

The second SDS was conducted in Ahmedabad, India [24], a tropical country. The experiment simulated site separation distances below 20 km, specifically, 15 km using an impact-type disdrometer manufactured by Disdromet (RD-80) to measure the three years of data from 2005 to 2007. The drop size distribution (DSD) was measured and presented in a time series and changed to the rain rate using the Bayesian technique; thus, the rain rate was converted to rain attenuation using the ITU-R P.618-10 rain attenuation model. The deduced SDG values are displayed in the graph of Figure 6 in [24]. The validity of the data from Greece and India is above 90%. Table 4 listed the parameters used in the investigations of the two SDSs.

TABLE 4. **Parameters of the measured SDG.**

Site	Frequency (GHz)	Distance (km)	E. Angle (Degree)	B. Angle (Degree)
NTUA-LTCP	19.701	36.5	46°	40°
India	20	15	50°	0°

The values of SDGs were extracted from these two SDSs as reported in their respective articles. The SDG values from

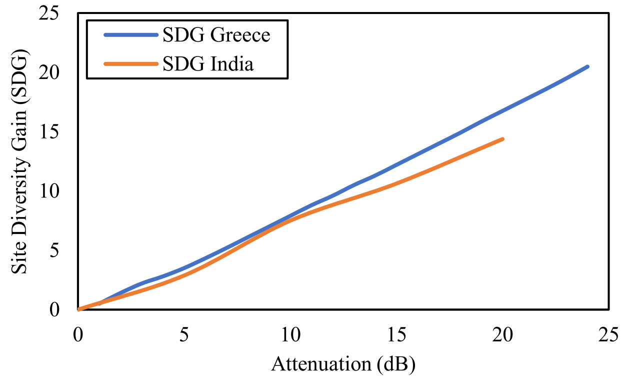

FIGURE 5. The extracted SDGs of Greece and India as shown in their articles [50] and [24], respectively.

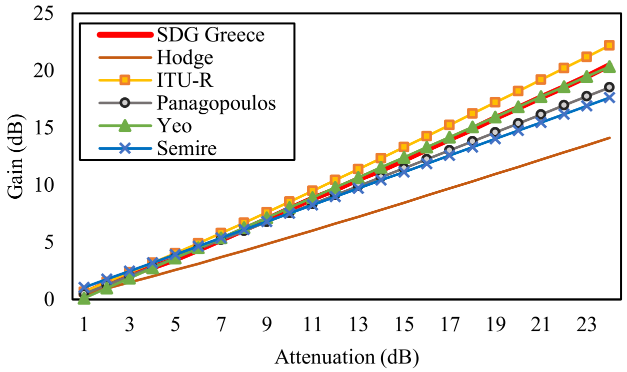

FIGURE 6. Performances of SDG prediction models on the SDG of NTUA-LTCP in Greece.

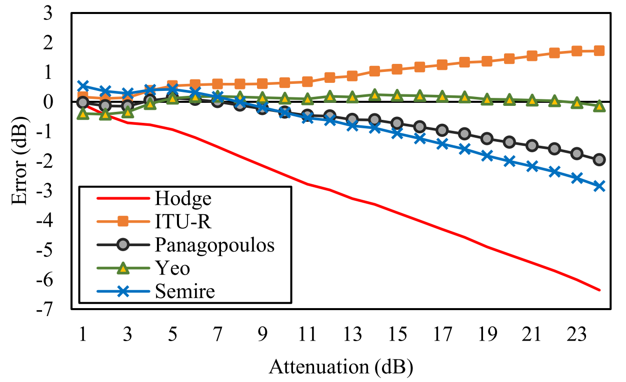

FIGURE 7. Errors of each SDG model compared with the measured SDG of NTUA-LTCP in Greece.

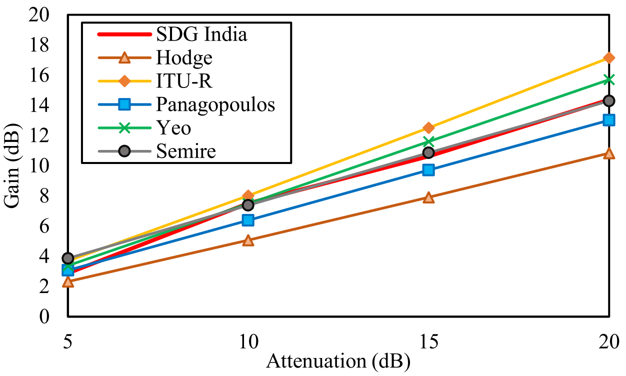

FIGURE 8. Performances of SDG prediction models on the measured SDG in India.

the SDS in Greece were obtained from the attenuation and joint attenuation graph of the NTUA-LTCP displayed in Figure 2 in [50]. Those SDG were extracted at attenuation of 1 dB to 24 dB. For the SDS in India, we measured the displayed SDG accordingly at attenuation of the 5 dB step directly from the graph of Figure 6 in [24]. Figure 5 depicted the SDGs in Greece and India after the extraction process.

This evaluation observes the flexibility of each SDG model's behavior on other SDS experiments than those used by the model's creators. A simple basic erroneous was used to compare those models, denoted as e_i, as displayed in (16). The subscript i is the number of test variables, up to N, which is the total number of tested values; that is, 24. Gp is the predicted gain, Gm is the measured gain, and e_T in (17) is the total error.

$$e_i = Gp_i - Gm_i \quad (16)$$

$$e_T = \sum_i^N e_i \quad (17)$$

Figure 6 shows a comparison between the model with SDGs in Greece. It is observed that the Yeo model can predict the closest comparison to the measured SDG, while the second closest seemed to be the ITU-R and Panagopoulos models, followed by the Semire model, and last, the Hodge model. Figure 7 shows the error values that have been calculated for each model for gain prediction in Greece. The Hodge model has shown an error graph far down the y-axis as the attenuation values increased. These negative values indicated that the prediction was far less than the measured gain. The Semire and Panagopoulos models also portrayed negative values but not far from the zero value of the y-axes; therefore, the errors were considered less than those in the Hodge model. The errors portrayed by the Yeo model were around the zero value of the y-axes; hence, the model seemed to successfully predict the closest value to the measured gain. The ITU-R model showed an increasingly positive value of errors; thus, the model is considered to overestimate the measured data.

Figure 8 shows the graph of the predicted values of each model upon the measured SDG at Ahmedabad, India. From the observation in the graph, the Semire model outperformed the other models. Panagopoulos and Yeo's model seemed to be the second closest to the measured data, followed by the ITU-R and the Hodge models. Figure 9 shows the errors of each model compared to the measured data. From the observations in the graph of errors in Figure 9, the Hodge model showed increasing errors far down to the y-axes in negative values as the attenuation increased. The negative values indicate that the gains predicted by the model were smaller than the measured gains. The Panagopoulos model was observed to predict almost accurate gain at an attenuation of 5 dB, but the gap slowly increased, showing the error in negative values as the attenuation increased.

Therefore, both the Hodge and Panagopoulos models are considered to underestimate the measured gain. The model of Semire displayed a larger gap than the other models at attenuation 5 dB with an error of almost 1 dB; then, for the rest of the

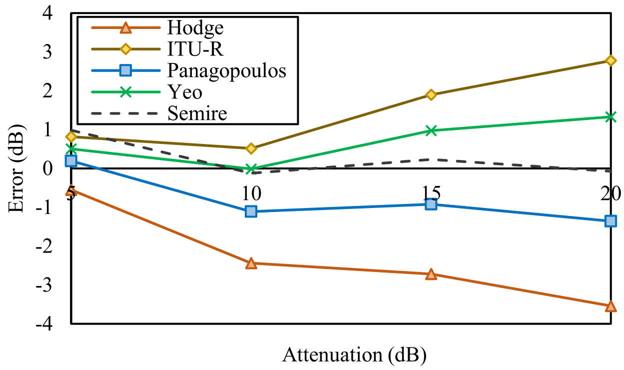

FIGURE 9. Errors of each SDG model compared with the measured SDG in India.

attenuation values, the model showed the lowest error, among the other models. The Yeo model showed a moderate gap at the first stage of attenuation, and then the error decreased at an attenuation of 10 dB. However, the model overpredicted the measured gain for the rest of the increasing attenuation values. Similarly, the ITU-R model portrayed positive error values and was considered to overpredict the gain more than that of the Yeo model as the attenuation increased.

TABLE 5. Total errors, e_T in dB, of each prediction model upon the SDG in Greece and India.

Sites	Hodge	ITU-R	Panagopoulos	Yeo	Semire
Greece	-74.86	21.98	-15.98	1.23	-20.10
India	-9.25	6.00	-3.20	2.80	1.02

Table 5 shows the total errors, e_T, exhibited by each model. For the measured gain in Greece, the Hodge model showed a total of 74.86 dB in the negative y-axis direction, which was the largest error in magnitude, while the Yeo model showed the least total errors among the other models, which was 1.23 dB. There was a large difference in total errors between the Yeo and Hodge models, which is 73.63 dB. The ITU-R model showed the second-largest total error, which was 21.98 dB, and exhibited a difference of 52.88 dB. The Semire model showed a total of 20.10 dB errors, and the Panagopoulos model had an error of 15.98 dB; both were in the negative y-axis direction. For the measured gain in India, once again, the Hodge model showed the largest accumulated error, which was 9.25 dB in the negative y-axis direction, while the Semire model showed the lowest accumulated errors compared with the other models. The difference between the Semire and Hodge models was 8.23 dB. The difference of total errors exhibited by the Semire model to the ITU-R model and Yeo model were 4.98 dB and 1.78 dB, respectively. The Panagopoulos model showed a difference of 2.18 dB in total errors from the Semire model, but the model went in the negative y-axis direction.

From the comparisons of each model to the measured gain obtained from the SDS of NTUA-LTCP in Greece, the Yeo model that had been created using local attributes of Singapore districts and terrain was observed to predict the closest values to the measured gain than the other temperate region-based models, such as the ITU-R, Panagopoulos, and Hodge models. The site separation distance of the SDS in Greece was beyond 20 km, which was 36.5 km; therefore, the ITU-R and Hodge models seemingly are not appropriate for the extent. The Panagopoulos model should be on the list of at least the one that shows the almost closest value to the gain, but it was not, and rather the model underestimated it.

For the comparisons of the measured gain obtained from the SDS in India, the model of Semire, which had been created using several Southeast Asian countries' attributes, was observed to predict the gain almost accurately. The site separation distance of the measured gain was 15 km, which was below 20 km, and the Hodge or ITU-R model should appropriately match at least, but they do not. This may have been caused by the attenuation log-normal curve in the tropics being different than that in the temperate region, a climate in which most data have been used to validate these models.

V. CONCLUSION

This article presents a detailed review structure of site diversity that consists of the concept and evolution of the currently existing site diversity gain (SDG) prediction models, namely, the Hodge, ITU-R, Panagopoulos, Semire, and Yeo models. The advantages and disadvantages of each SDG prediction model have been presented, as well as the SDG past studies' summarization concerning the tropical region. Thus, this article brings the main issue in developing an SDG prediction model that is related to the parameters that contributed to the SDG. Those are site separation distance, link frequency, antenna elevation angle, and baseline orientation angle. The other issue that has been highlighted also is that the set of validation data used to compare each of the models in the literature, that may consist of unbalanced parameters in terms of site separation distance employed by the list of data, consequently giving unjustice assessment to some of the models being evaluated.

As being concluded from the past studies, the site separation distance is the major parameter that affects the SDG. Some studies recognized frequency and baseline angle as contributors, while some did not. While each SDG prediction model was designed to correlate those parameters in different ways according to the findings; this article utilizes two site diversity experiments conducted in two different climates, which are in Greece of a temperate region and in India with a tropical climate, to be compared with the existing SDG prediction models. The outcome of the comparison shows that the Hodge and ITU-R models did not suit the measured gain obtained in India, which employed a site separation distance of 15 km, although they are pronounced to be appropriate for site separation distances below 20 km. This is because these models were validated in temperate regions, while India is in the tropics. Similarly, the Yeo model, although developed in a tropical region, suits the measured gain of Greece, which employed site separation distances beyond 20 km, to which the Panagopoulos model failed to adhere.

Therefore, the SDG prediction models in the literature show a large gap that should be filled in because the behavior of the gain may be influenced by many factors, such as the climate. Consequently, based on the survey presented in this article, the validation of any proposed model using a balanced set of data from a variety of climates is recommended. Alternatively, a specific prediction model for specific climates may be proposed.

REFERENCES

[1] L. J. Ippolito, "Rain fade mitigation," in *Satellite Communications Systems Engineering: Atmospheric Effects, Satellite Link Design and System Performance*, 2nd ed. West Sussex, U.K.: Wiley, 2017, pp. 205–233.

[2] P. M. Kalaivaanan, A. Sali, R. S. A. R. Abdullah, S. Yaakob, M. J. Singh, and A. M. Al-Saegh, "Evaluation of Ka-band rain attenuation for satellite communication in tropical regions through a measurement of multiple antenna sizes," *IEEE Access*, vol. 8, pp. 18007–18018, 2020, doi: 10.1109/ACCESS.2020.2966873.

[3] J. E. Allnut, "Satellite earth station antenna systems and system design," in *Handbook of Satellite Applications*, 2nd ed. Cham, Switzerland: Springer, 2017, pp. 567–601, doi: 10.1007/978-3-319-23386-4_20.

[4] O. O. Obiseye, O. Adetan, and S. I. Tunji, "Recent update on one-minute rainfall rate measurements for microwave applications in Nigeria," *Int. J. Wireless Commun. Mobile Comput.*, vol. 2, no. 3, pp. 33–39, Jun. 2015, doi: 10.11648/j.wcmc.20150303.12.

[5] H. Fukuchi and T. Saito, "Novel mitigation technologies for rain attenuation in broadband satellite communication system using from Ka- to W-band," in *Proc. 6th Int. Conf. Inf., Commun. Signal Process.*, 2007, pp. 1–5, doi: 10.1109/ICICS.2007.4449874.

[6] X. Boulanger, B. Gabard, L. Casadebaig, and L. Castanet, "Four years of total attenuation statistics of earth-space propagation experiments at Ka-band in Toulouse," *IEEE Trans. Antennas Propag.*, vol. 63, no. 5, pp. 2203–2214, May 2015, doi: 10.1109/TAP.2015.2407376.

[7] R. M. Zali and M. J. Singh, "Perbandingan model jangkaan bagi taburan sintilasi troposferik untuk frekuensi jalur ku di Malaysia," *Jurnal Kejuruteraan*, vol. 24, pp. 1–6, Dec. 2012.

[8] X. Boulanger, B. Benammar, and L. Castanet, "Propagation experiment at Ka-band in French Guiana: First year of measurements," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 2, pp. 241–244, Feb. 2019, doi: 10.1109/LAWP.2018.2887280.

[9] M. Rytir, M. Cheffena, P. A. Grotthing, L. E. Bråten, and T. Tjelta, "Three-site diversity at Ka-band satellite links in Norway: Gain, fade duration, and the impact of switching schemes," *IEEE Trans. Antennas Propag.*, vol. 65, no. 11, pp. 5992–6001, Nov. 2017, doi: 10.1109/TAP.2017.2751667.

[10] L. Castanet, A. B. Alamañac, and M. Bousquet. *Interference and Fade Mitigation Techniques for Ka and Q/V Band Satellite Communication Systems*. Accessed: Nov. 13, 2020. [Online]. Available: http://morse.uml.edu/Activities.d/Summer5/PAPERS/KC/pm-5-002.pdf

[11] S. Harika, S. Nagarjuna, T. V. Naveen, G. S. Harshanth, K. C. S. Kavya, and S. K. Kotamraju, "Analysis of rain fade mitigation using site diversity technique in southern tropical region of India," *Int. J. Eng. Technol.*, vol. 7, no. 1, pp. 622–626, 2018.

[12] K. Salazar, B. Ramos, J. Brito, and M. D'Amico, "Performance of multiple-site diversity and its relationship with time diversity in tropical regions," in *Proc. IEEE 10th Latin-Amer. Conf. Commun. (LATINCOM)*, Guadalajara, Mexico, Nov. 2018, pp. 1–5, doi: 10.1109/LATINCOM.2018.8613230.

[13] C. Capsoni, M. D'Amico, R. Nebuloni, and C. Riva, "Performance of site diversity technique estimated from time diversity," in *Proc. 5th Eur. Conf. Antennas Propag. (EUCAP)*, Apr. 2011, pp. 1463–1466.

[14] J. S. Mandeep and K. Tanaka, "Effect of atmospheric parameters on satellite link," *Int. J. Infr. Millim. Waves*, vol. 28, no. 10, pp. 789–795, Aug. 2007.

[15] L. Luini, C. G. Riva, L. Emiliani, and J. Nessel, "Modeling the impact of rain and clouds on earth-space site diversity systems," *IEEE Trans. Antennas Propag.*, vol. 67, no. 1, pp. 475–483, Jan. 2019, doi: 10.1109/TAP.2018.2876712.

[16] A. Vilhar, G. Kandus, A. Kelmendi, U. Kuhar, A. Hrovat, and M. Schönhuber, "Three-site Ka-band diversity experiment performed in Slovenia and Austria," in *9th Eur. Conf. Antennas Propag. (EuCAP)*, Lisbon, Portugal, Apr. 2015, pp. 1–5.

[17] I. M. Rafiqul, M. L. Altajjar, M. S. Habib, K. Abdullah, M. M. Rashid, and K. L. Bashar, "Frequency diversity improvement factor for rain fade mitigation in Malaysia," in *Proc. IEEE Int. WIE Conf. Electr. Comput. Eng. (WIECON-ECE)*, Dhaka, Bangladesh, Dec. 2015, pp. 159–163, doi: 10.1109/WIECON-ECE.2015.7443886.

[18] D. B. Hodge, "An improved model for diversity gain on earth-space propagation paths," *Radio Sci.*, vol. 17, no. 6, pp. 1393–1399, 1981, doi: 10.1029/RS017i006p01393.

[19] A. V. Bosisio and C. Riva, "A novel method for the statistical prediction of rain attenuation in site diversity systems: Theory and comparative testing against experimental data," *Int. J. Satell. Commun.*, vol. 16, no. 1, pp. 47–52, 1998.

[20] D. B. Hodge, "An empirical relationship for path diversity gain," *IEEE Trans. Antennas Propag.*, vol. AP-24, no. 2, pp. 250–251, Mar. 1976, doi: 10.1109/TAP.1976.1141304.

[21] F. Samat and J. S. Mandeep, "Rain attenuation at tropical region site diversity gain models sensitivity," *Indonesian J. Electr. Eng. Informat.*, vol. 7, no. 3, pp. 472–483, 2019, doi: 10.11591/ijeei.v7i3.956.

[22] L. Luini and C. Capsoni, "A rain cell model for the simulation and performance evaluation of site diversity schemes," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 1327–1330, 2013, doi: 10.1109/LAWP.2013.2285400.

[23] C. I. Kourogiorgas, A. D. Panagopoulos, and J. D. Kanellopoulos, "On the earth-space site diversity modeling: A novel physical-mathematical outage prediction model," *IEEE Trans. Antennas Propag.*, vol. 60, no. 9, pp. 4391–4397, Sep. 2012.

[24] S. Das and A. R. Jameson, "Site diversity prediction at a tropical location from single-site rain measurements using a Bayesian technique," *Radio Sci.*, vol. 53, no. 6, pp. 830–844, Jun. 2018, doi: 10.1029/2018RS006597.

[25] A. Kelmendi, C. Kourogiorgas, A. Hrovat, A. D. Panagopoulos, G. Kandus, and A. Vilhar, "Prediction of joint rain attenuation statistics induced on earth–satellite multiple site diversity systems using Gaussian copula," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 95–98, 2017, doi: 10.1109/LAWP.2016.2557960.

[26] *Propagation Data and Prediction Methods Required for the Design of Earth-Space Telecommunication Systems*, document ITU-R P.618-13, Geneva, Switzerland, Dec. 2017.

[27] M. Luglio, R. Mancini, C. Riva, A. Paraboni, and F. Barbaliscia, "Large-scale site diversity for satellite communication networks," *Int. J. Satell. Commun.*, vol. 20, no. 4, pp. 251–260, Jul. 2002, doi: 10.1002/sat.723.

[28] A. V. Bosisio, C. Capsoni, and E. Matricciani, "Comparison among prediction methods of site diversity system performances," in *Proc. 8th Int. Conf. Antennas Propag.*, Mar./Apr. 1993, pp. 60–63.

[29] 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 Trans. Antennas Propag.*, vol. 53, no. 7, pp. 2307–2313, Jul. 2005, doi: 10.1109/TAP.2005.850762.

[30] C. Nagaraja and I. E. Otung, "Statistical prediction of site diversity gain on earth-space paths based on radar measurements in the UK," *IEEE Trans. Antennas Propag.*, vol. 60, no. 1, pp. 247–256, Jan. 2012, doi: 10.1109/TAP.2011.2167896.

[31] K. I. Timothy, J. T. Ong, and E. B. L. Choo, "Performance of the site diversity technique in Singapore: Preliminary results," *IEEE Commun. Lett.*, vol. 5, no. 2, pp. 49–51, Feb. 2001, doi: 10.1109/4234.905932.

[32] Q. W. Pan, J. E. Allnut, and C. Tsui, "Evaluation of diversity and power control techniques for satellite communication systems in tropical and equatorial rain climates," *IEEE Trans. Antennas Propag.*, vol. 56, no. 10, pp. 3293–3301, Oct. 2008.

[33] A. K. Shukla, R. Bijoy, D. Saurabh, A. R. Charania, K. S. Kavaiya, B. Kalyan, and K. S. Dasgupta, "Micro rain cell measurements in tropical India for site diversity fade mitigation estimation," *Radio Sci.*, vol. 45, no. 1, pp. 1–13, Feb. 2010, doi: 10.1029/2008RS004093.

[34] B. Roy, A. Shukla, and M. R. Sivaraman, "Micro scale site diversity over a tropical site in India and evaluation of diversity gain with synthetic storm technique," *Indian J. Radio Space Phys.*, vol. 40, no. 4, pp. 211–217, Aug. 2011.

[35] J. X. Yeo, Y. H. Lee, and J. T. Ong, "Performance of site diversity investigated through RADAR derived results," *IEEE Trans. Antennas Propag.*, vol. 59, no. 10, pp. 3890–3898, Oct. 2011, doi: 10.1109/TAP.2011.2163770.

[36] J. X. Yeo, Y. H. Lee, and J. T. Ong, "Site diversity gain at the equator: Radar-derived results modeling in Singapore," *Int. J. Satell. Commun. Netw.*, vol. 33, no. 2, pp. 107–118, Mar. 2015, doi: 10.1002/sat.1074.

[37] R. J. Acosta, J. Morse, M. Zemba, and J. Nessel, "Two years of site diversity measurements in Guam, USA," in *Proc. 18th Ka Broadband Commun., Navigat. Earth Observ. Conf.*, Ottawa, ON, Canada, Sep. 2012, pp. 1–8. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120016399.pdf

[38] 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," *Math. Softw. Eng.*, vol. 2, no. 2, pp. 105–113, 2016.

[39] A. I. O. Yussuff, N. Hamzat, and N. H. H. Khamis, "Site diversity technique application on rain attenuation for Lagos," *Indonesian J. Electr. Eng. Informat.*, vol. 5, no. 1, pp. 77–84, Mar. 2017, doi: 10.11591/ijeei.v5i1.262.

[40] M. D'Amico, A. Manzoni, B. Ramos, and J. L. Santos, "Performance of equatorial multiple-site diversity systems evaluated from rain rate time series," in *Proc. 11th Eur. Conf. Antennas Propag. (EUCAP)*, Mar. 2017, pp. 45–49, doi: 10.23919/EuCAP.2017.7928216.

[41] F. A. Semire, R. Mohd-Mokhtar, W. Ismail, N. Mohamad, and J. S. Mandeep, "Evaluation of site diversity rain attenuation mitigation technique in South-East Asia," *Acta Astronautica*, vol. 96, pp. 303–312, Mar. 2014, doi: 10.1016/j.actaastro.2013.11.034.

[42] 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," *Ann. Geophys.*, vol. 33, no. 3, pp. 321–331, Mar. 2015, doi: 10.5194/angeo-33-321-2015.

[43] I. M. Rafiqul, A. K. Lwas, N. Muhammad, M. Singh, R. Adawiyah, and A. Ismail, "Analysis of rain fade mitigation using site diversity on earth-to-satellite microwave links at ku-band," in *Proc. 5th Brunei Int. Conf. Eng. Technol. (BICET)*, Bandar Seri Begawan, Brunei, 2014, pp. 1–5, doi: 10.1049/cp.2014.1104.

[44] I. M. Rafiqul, M. H. Habaebi, I. M. Haidar, A. K. Lwas, A. Zyoud, and M. Singh, "Rain fade mitigation on earth-to-satellite microwave links using site diversity," in *Proc. IEEE 12th Malaysia Int. Conf. Commun. (MICC)*, Kuching, Malaysia, Nov. 2015, pp. 186–191, doi: 10.1109/MICC.2015.7725431.

[45] M. R. Islam, A. K. Lwas, and M. H. Habaebi, "Site diversity gain for earth-to-satellite links using rain intensity measurement," *Indonesian J. Electr. Eng. Informat.*, vol. 5, no. 4, pp. 330–338, Dec. 2017, doi: 10.11591/ijeei.v5i4.364.

[46] H. Y. Lam, L. Luini, J. Din, C. Capsoni, and A. D. Panagopoulos, "Performance of site-diversity satellite communication systems in equatorial Malaysia investigated through weather radar data," in *Proc. 9th Eur. Conf. Antennas Propag. (EuCAP)*, Lisbon, Portugal, Apr. 2015, pp. 1–4.

[47] S. L. Jong, H. Y. Lam, J. Din, and M. D. Amico, "Investigation of Ka-band satellite communication propagation in equatorial regions," *ARPN J. Eng. Appl. Sci.*, vol. 10, no. 20, pp. 9795–9799, 2015. [Online]. Available: https://core.ac.uk/download/pdf/42955742.pdf

[48] F. Samat and M. J. Singh, "Site diversity performance in Ka band using a 7.3-m antenna diameter at tropical climate: A comparison of prediction models," *Acta Geophysica*, vol. 68, no. 4, pp. 1213–1221, Aug. 2020, doi: 10.1007/s11600-020-00451-y.

[49] F. Samat, M. J. Singh, A. Sali, and P. M. Kalaivaanan, "Observation of site diversity gain dependency on separation distance using an attenuation-dependent logarithmic model in a tropical region," *IEEE Access*, vol. 9, pp. 33994–34006, Feb. 2021, doi: 10.1109/ACCESS.2021.3056183.

[50] A. Z. Papafragkakis, C. I. Kourogiorgas, and A. D. Panagopoulos, "Site-diversity Ka-band satellite propagation campaign in Attica, Greece, using Alphasat: First 2 years' results," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 10, pp. 2115–2119, Oct. 2019, doi: 10.1109/LAWP.2019.2938059.

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