

Site Diversity Gain at the Equator: Radar-Derived Results and Modeling in Singapore

J. X. Yeo^{1,*}, Y. H. Lee¹, and J. T. Ong²

¹ Nanyang Technological University, Singapore
² C2N Pte. Ltd., Singapore

ABSTRACT

Site diversity is an effective rain attenuation mitigation technique, especially in the tropical region where high rainfall rates are common. According to our previous study, site diversity gain is found to be dependent on the site separation distance and path elevation angle while it is independent of signal frequency, baseline angle and polarization angle. Therefore, using 28 months of Radar data, a simple site diversity gain prediction model is proposed. The proposed model is compared with the existing ITU-R models. The seasonal wind direction, another factor that might affect the site diversity gain prediction model, is shown to have negligible effect on site diversity gain. Triple-site diversity is also investigated and although it is found to provide gain improvement over dual-site diversity, this gain improvement is too little to justify for the cost of setting up an additional site. This study is useful for the implementation of site diversity as a rain attenuation mitigation technique in the tropical region. Copyright © 20xx John Wiley & Sons, Ltd.

KEY WORDS: Site Diversity, Earth-Satellite Communication

1. INTRODUCTION

In order to overcome the problem of spectrum congestion, the Ka and higher frequency bands are becoming increasingly attractive for satellite communications. However, signals with higher frequency suffer higher rain attenuation, especially in the tropical region where heavy rain events are common. These heavy rainfalls can cause outage of signals and therefore interruption of satellite services. At a common tropical rain rate of 100 mm/hr, an attenuation of up to 10 dB per km is observed for up to a period of 10 minutes in the Ka-band frequency of 20 GHz [1], [2]. In such situations, common mitigation techniques such as power control are not sufficient to counteract the large signal fade. The dynamic range generally considered for power variation is about 10 dB [3]. Site diversity is found to be one of the most effective fade mitigation techniques used to counteract rain attenuation [4]. A site diversity satellite system usually will consist of two or more spatially separated ground stations. The concept of site diversity is based on the fact that rain seldom occurs simultaneously on two spatially separated slant paths. That is to say, if there is an alternative path, it is significantly less likely to rain along both slant paths as compared to rain along an individual propagation path. The rain attenuation suffered by the link can thus be reduced or eliminated.

*Correspondence to: J. X. Yeo, Communication Research Lab, Division of Communications Engineering, School of Electrical and Electronic Engineering, Nanyang Technological University (NTU), 50 Nanyang Avenue, Singapore 639798.
†E-mail: jxyeo@ntu.edu.sg

The site diversity gain prediction models can be classified into two categories; physical models; or regression models. Physical models are based on the understanding of the rain process, such as rain cell structure and vertical structure of precipitation. EXCELL [5], Matricciani [6] and Paraboni-Barbaliscia [7] models are well known physical prediction models for site diversity performance. The Hodge [8] model is a regression model based on the regression fitting of the available rain attenuation statistics. The Paraboni-Barbaliscia and Hodge models have both been adopted by the current ITU-R recommendation [9] for predicting the site diversity gain. Most of these initial studies on site diversity are carried out in temperate regions [10]-[12]. The ITU-R Hodge model provides a diversity gain model that is dependent on single site attenuation, frequency, site separation distance, elevation angle and baseline angle.

Initial propagation studies for the Ku-band and/or higher frequency bands in the tropical region have only started in the past few years. In 2001, some preliminary results on site diversity in the tropical country of Singapore were reported [13]. Good agreement between the ITU-R predictions and measured diversity gain has been observed at 11.198 GHz with a site separation of 12.3 km. In Pan [3], experiments conducted in Lae, Papua, New Guinea showed that at least 5 dB site diversity gains can be obtained in the tropical region [3]. In 2010, the study of micro rain cell measurements was conducted in India [14]. They showed that site diversity can be effective for short distance site separation due to the existence of micro rain cells. In 2011, the validity of the ITU-R model when applied to the tropical region is examined [15]. The effects of frequency, site separation distance, elevation angle, baseline angle, polarization angle and wind direction on diversity gain are examined. Contrary to the proposed ITU-R Hodge model, results show that the diversity gain is independent of frequency, baseline angle but is dependent on the single site attenuation, site separation distance and elevation angle. The seasonal wind direction is also found to affect the diversity gain because of its effect on the movement and the shaping of the rain clouds.

In this paper, a site diversity gain prediction model that is only dependent on the separation distance and elevation angle is proposed. This is done based on the full volumetric weather Radar data obtained from the Singapore Changi weather station. The results are compared with both the ITU-R Hodge model, ITU-R (H) and the ITU-R Paraboni-Barbaliscia model, ITU-R (P-B).

Section 2 provides a description of the Radar system used for the analysis. Section 3 shows the formulas for the calculation of path rain attenuation and site diversity gain. In section 4, the procedures used to calculate the diversity gain are described in detail. The diversity gain prediction model is proposed in this section. The effect of monsoon season and performance of triple-site diversity are also examined in section 4. Finally, the conclusions are given in section 5 of the paper.

2. RADAR DATASETS

The Radar dataset used in this study is collected at the Changi weather station (1.3512° N, 103.97° E) on the east coast of Singapore. The Radar is operating at the S-band frequency of 2.71 GHz. It performs a full volume scans every 5 min. The maximum range of the scanning rays is at least 120 km for elevation angles from 0.1° to 40° . Other details of the Radar are given in [15]. Full volumetric data for the year 2003 and for 16 months from May 2010 to August 2011 will be used to derive the statistical prediction model for the site diversity gain.

3. THEORETICAL FORMULATION AND MODELS

Figure 1 shows the overall map of Singapore, which is about 25 km by 45 km. For this site diversity study, the tropical island city of Singapore is divided by grids. The choice of the grid size is based on our previous study and the Radar resolution. From our previous study [15], more than 80% of the rain events in Singapore

are convective with a rain cell size of less than 15 km. For the benefit of uniform regression analysis, square grids that are less than 15 km apart are chosen. Based on the gating resolution of the Radar system, the smallest grid size possible is 250 m. Smaller grids give more precise results, however, they result in an increase in computation time. Therefore, in this study, square grid size of $5 \times 5 \text{ km}^2$ is used. This is sufficient for the site diversity analysis yet has a reasonable computation time.

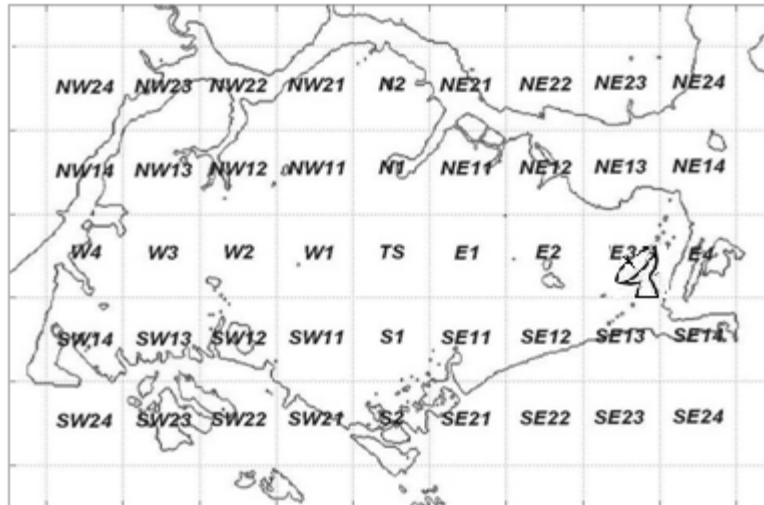


Figure 1. Singapore Map with the Partition of 45 Grids.

The center of the Singapore Island is Thomson and is denoted by the grid labeled *TS* in Figure 1. The square *E3* (position of Radar, 1.3512°N , 103.97°E , 3rd grid right of *TS*) for example, is located 15 km east of *TS*. *W3* is 15 km west of *TS*, and is the location of Nanyang Technological University, the university campus. In this paper, 5 sites, representative of the north, south, east, west and central regions of Singapore, the sites *N2*, *S2*, *E4*, *W3* and *TS* will be used as reference sites for discussion and analysis of site diversity.

Figure 2 shows the monthly cumulative distribution function (CDF) of rainfall rate of the five reference sites in the month of July 2010. As shown in Figure 2, at 0.1% of time, the rainfall rate at site *E4* and *N2* (22 km apart) are 94 mm/hr and 167 mm/hr respectively. The corresponding single site attenuation for these rainfall rates are 14 dB and 37 dB respectively for frequency of 20 GHz and 50° elevation angle. This shows that despite Singapore's small size, the rain distributions among the island can differ significantly especially on a monthly basis. Therefore, it is feasible to employ site diversity as a rain attenuation mitigation technique.

In order to derive the rain attenuation from the measured data obtained from the Radar system, the point rain rate, R_i , needs to be obtained from the reflectivity to rainfall rate (Z-R) relationship. The Z-R relationship is used to convert the Radar reflectivity values, Z , into rainfall rate, R , at every pixel along the earth-space propagation path. The Marshall-Palmer's Z-R relationship of $Z = 200 R^{1.6}$ is optimum for general stratiform precipitation often experienced in temperate regions, however, it tends to underestimate the rainfall rate in the tropical regions such as Singapore. Rosenfeld's Z-R relationship [16] that shown in (1) is widespread used to get the optimum prediction of convective rain often experienced in tropical regions.

$$Z = 250 \cdot R^{1.2} \quad (1)$$

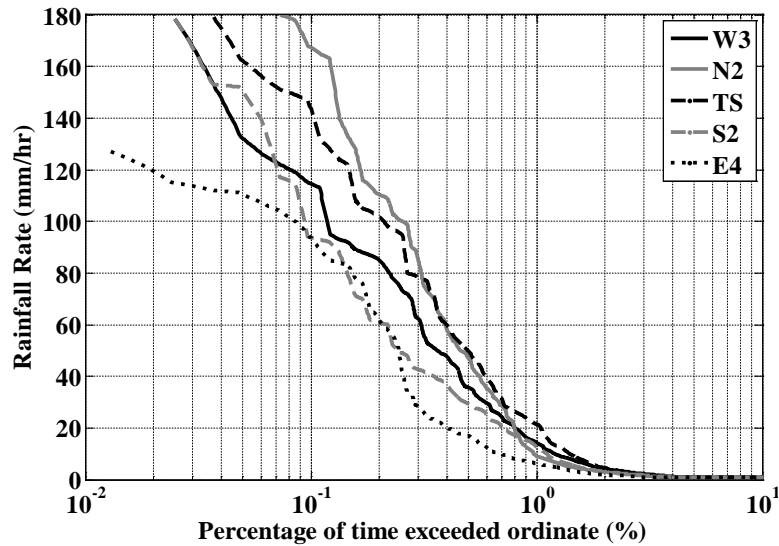


Figure 2. Monthly CDF of Rainfall Rate at 5 Reference Sites for July 2010.

Figure 3 shows the CDF of measured path attenuation of WINDS satellite at the site W3 and CDFs of the predicted attenuation from Radar by using Marshall-Palmer and Rosenfeld Z-R Relationships. The WINDS satellite is located at 143° E has a beacon frequency of 18.9 GHz, elevation angle of the path is 44.5° , and LHCP polarization. Other information of WINDS beacon receiver can be found in [17]. As stated above, the Marshall-Palmer Z-R relationship tends to underestimate the rainfall rate in tropical region and therefore underestimate the path attenuation. The error of the attenuation prediction from Rosenfeld's Z-R relationship is less than 5 dB for beacon attenuation up to 30 dB. Therefore, the Rosenfeld's Z-R relationship will be used in this paper.

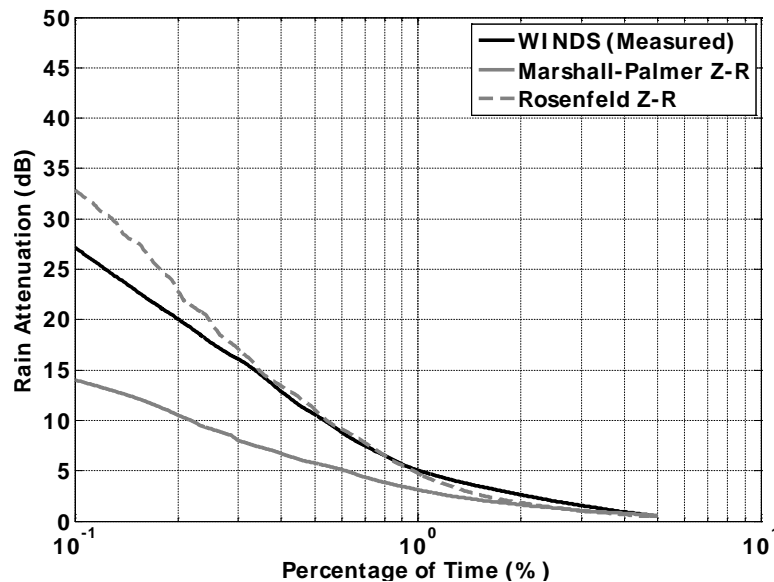


Figure 3. CDFs Comparison of Attenuation along WINDS Satellite Propagation Path and the Predicted Attenuation from Radar by using Marshall-Palmer and Rosenfeld Z-R Relationships.

Once the point rain rate, R_i , is obtained, the slant path attenuation can then be derived using (2). In order to calculate the rain attenuation along the slant path between the earth stations to the satellites, the path

attenuation associated with each pixel is calculated and then integrated over the length of the slant path using (2). The earth-space path attenuation A is calculated through the numerically summation of:

$$A = \sum_{i=0}^n k R_i^\alpha \cdot L_i \quad (2)$$

where $L = h_R / \sin \theta$ is the path length affected by rain, θ is the link elevation angle, h_R is the fixed yearly mean rain height, derived from ITU-R Rec. P.839-3 [18]. The coefficients of specific attenuation, k and α , can be obtained from the ITU-R Rec. P.838-3 [19], and is dependent on the link elevation angle, the radiowave frequency and the polarization. In (2), R_i and L_i are the point rain rate value and pixel path length at each i^{th} pixel along the slant path between the earth station and the satellite. Therefore, the transmission link performance is strongly dependent on the precipitation characteristics along the slant path and affects the system performance significantly.

The CDF of the Radar calculated attenuation using (1) and (2) are compared with both the path attenuation of the Ka-band (18.9 GHz) and Ku-band (12.75 GHz) beacon signals. It is found that the prediction error is less than 5 dB for the beacon attenuation up to 30 dB. That is much better than the prediction performance from the attenuation calculated by Marshall-Palmer's Z-R relationship which underestimates the attenuation by more than 10 dB).

The gain G offered by a two-site diversity system, with separation D between the stations, can be calculated as [8]:

$$G(D, A_S) = A_S(P) - A_J(D, P) \quad (3)$$

where A_S is the attenuation suffered by the single site reference station and A_J is the joint site attenuation after applying selection combining. Selection combining is performed by selecting the minimum attenuation of the reference site and the diversity site. The site diversity gain at the time probability level P is the difference of the equi-probability attenuation of A_S and A_J .

For the earth-space path with the frequency of 20 GHz and a 50° elevation angle, the CDF of the rain attenuation at sites $W3$ and $SE11$ is shown in Figure 4. The CDF of rain attenuation after applying selection combining diversity for the two sites is also shown in Figure 4. For satellite communication applications, the Ku or Ka band frequency usually provide link availability of 99.7% to 99.9% of the time [20]-[21], which corresponds to a lost in satellite connectivity for 0.1% to 0.3% of the time. Therefore, for an application based study, the time percentage of 0.1% is used. As can be seen in Figure 4, the diversity gain at 0.1% of the time is 39.5 dB with reference to the reference site, $W3$. The site diversity provides significant improvement in both performance and availability of the system. When site diversity is implemented with other fade mitigation techniques such as power control, the effect of rain fade can be significantly reduced or even eliminated.

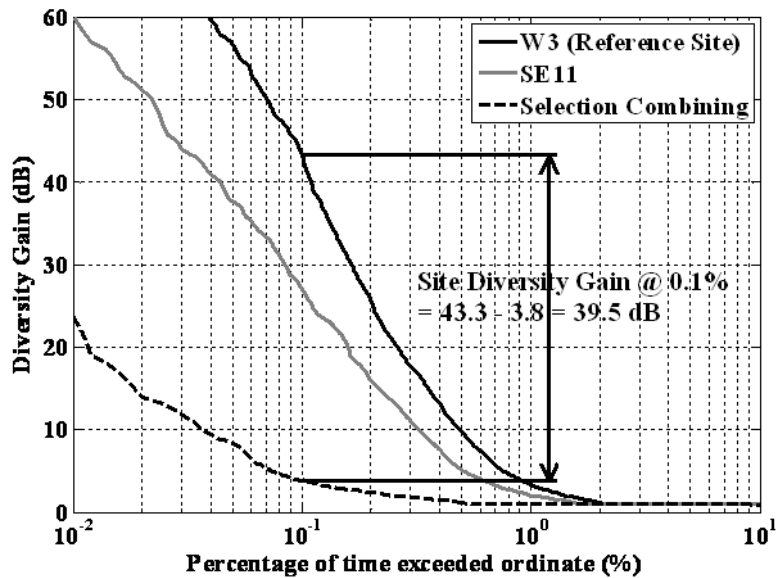


Figure 4. CDF of Attenuation of Single Site $W3$ & $N2$ and Selection Combining of Two Sites for 28 months.

In Section 4, the diversity gain simulated based on Radar data is compared with the ITU-R Hodge model and the ITU-R Paraboni-Barbaliscia model. Hodge model specifies that the site diversity gain is dependent on a number of factors; single site attenuation, A ; site separation distance, D ; frequency, f ; elevation angle, θ , and baseline angle, Ψ . However, as discussed in detail in [15], the site diversity gain is found to be only dependent on the single reference site attenuation, A_S ; site separation distance, D and elevation angle, θ . Therefore, in this paper, a simple empirical site diversity gain prediction model is proposed in Section 4.1.

4. RESULTS AND DISCUSSION

From the analysis results of [15], the site diversity gain depends on the site separation distance, elevation angle and perhaps the seasonal wind direction. Therefore, a site diversity gain model is proposed in this section.

Besides that, the feasibility of the triple site diversity will also be investigated.

4.1. Site Diversity Gain Prediction Model

To derive the site diversity model, the slant path attenuation for any path within the scanning volume of the Radar is simulated using (2). In our analysis, the 45 sites labeled in Figure 1 are selected as earth stations. The Radar reflectivity along the earth-space path with elevation angles of 10° , 30° , 50° , 70° and 90° at the 45 stations are extracted to calculate the attenuation for different frequencies. The frequency ranges from 10 GHz to 30 GHz at intervals of 2.5 GHz are examined. Therefore, for each of the 45 sites, 5 elevation angles at 9 different frequencies are simulated. This amounts to a total of 2025 simulated paths. All 2025 simulated slant path attenuations are used in our site diversity gain analyses and modeling.

In our previous study [15], the site diversity gain of specific single site attenuation is found to depend on the site separation distance and the elevation angle. Therefore, it can be concluded from [15] that the site diversity gain is a function of three factors: (1) the reference site attenuation, (2) the site separation distance and (3) the slant path elevation angle. Figure 5 shows the relations of diversity gain with each of the three factors while keeping the other two factors constant. From the curves, it is found that diversity gain increases

exponentially with site separation distance, D , and elevation angle, θ , whereas it increases linearly with the reference site attenuation, A_S .

By choosing 5 reference sites distributed over the island of Singapore at $W3$, TS , $E4$, $N2$, $S2$ and by using the statistical values over 28 months of Radar data and 2025 hypothetical slant paths, the proposed model for site diversity gain, G is derived as (4).

$$G = (-0.78 + 0.88A_S)(1 - e^{-0.18D})(1 + e^{-0.14\theta}) \quad (4)$$

As seen in (4), diversity gain has a linear relationship with the single reference site attenuation, A_S , and an exponential relationship with the site separation distance, D , and slant path elevation angle, θ .

Figure 6 shows the diversity gain between sites $W3$ and $SE11$, 20.6 km apart, at the frequency of 20 GHz and an elevation angle of 50° . The gain calculated using the proposed model in (4) is found to fit very well with the Radar measured results. This shows that the diversity gain is dependent on only the reference site attenuation, site separation distance and elevation angle, and is independent of the frequency and baseline angle, contrary to the ITU-R Hodge model. The ITU-R Hodge model, ITU-R (H), and ITU-R Paraboni-Barbaliscia model, ITU-R (P-B), are also plotted in Figure 6 for comparison and analysis. It is found that the ITU-R Hodge model tends to underestimate the diversity gain on this particular dataset. This is consistent with the findings presented in [15]. The ITU-R Paraboni-Barbaliscia model is a physical model that requires the CDF of point rainfall rate and single site attenuation as the input to the model. Therefore, the model's prediction performance is comparable with the proposed model.

In order to examine the accuracy of the proposed model as compared to the two ITU-R models, the root mean squared error is tabulated in Table 1.

With the concept of Relative Diversity Gain introduced in [22], [6] and defined as: $RDG = G/A_S$, the test variable for percentage error is given by:

$$Error = (RDG_{Predicted} - RDG_{Radar}) * 100\% \quad (5)$$

Table I shows the comparison of RMS error of RDG in percentages between the proposed model, the ITU-R Hodge model and the ITU-R Paraboni-Barbaliscia model with different reference sites. Figure 7 shows the CDF of the error of RDG for the simulated hypothetical slant paths, which includes slant paths with different elevation angles from 10° to 90° . From Table 1 and Figure 7, it can be seen that the error is significantly reduced with the proposed model as compared to the Hodge model. This shows that the proposed model can better predict the diversity gain as compared to the ITU-R Hodge model. The physical

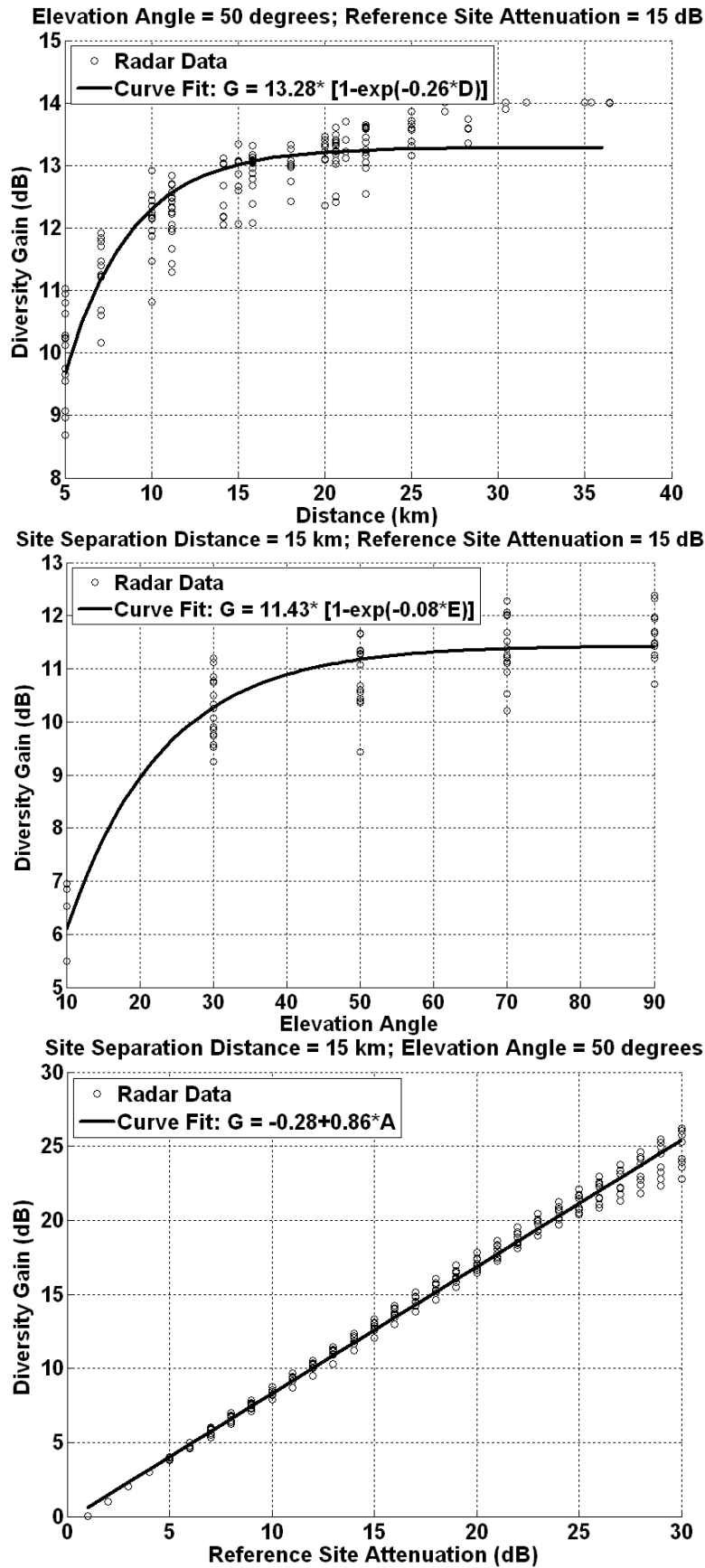


Figure 5. Effect of Site separation Distance, Elevation Angle, and Single Site Attenuation on the prediction of Site Diversity Gain.

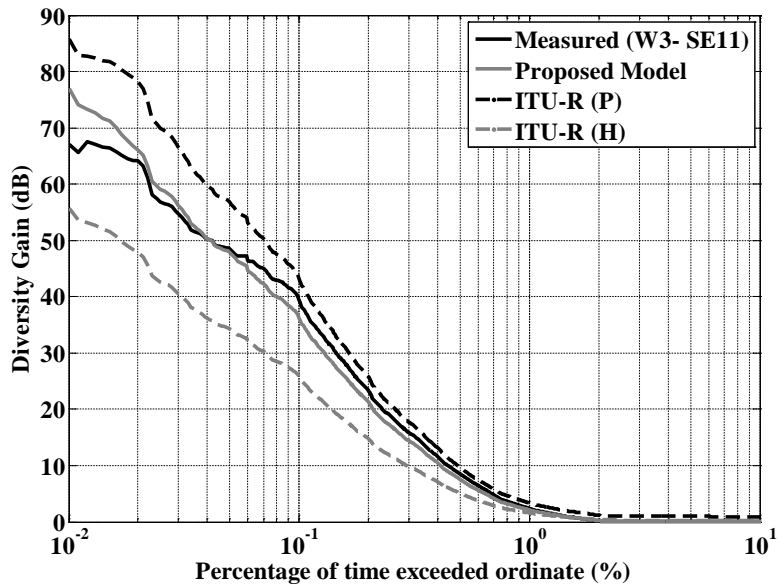


Figure 6. Performance of Site Diversity Gain Prediction Model.

ITU-R Paraboni-Barbaliscia model performs better than the ITU-R Hodge model and performs consistently worse than the proposed model. From Figure 7, for 90% of the time, the predicted error of the proposed model is 12.5%; whereas the predicted error of the ITU-R Paraboni-Barbaliscia model and the ITU-R Hodge model are 37% and 35% respectively.

Therefore, it is shown that, not only is the proposed model able to predict the diversity gain to a higher accuracy, it is also a simple model that only depends on 3 of the 5 factors that the ITU-R Hodge model uses. It is not necessary to take into consideration the frequency and baseline angle in the site diversity gain prediction model.

Table I. Site Diversity Gain Prediction Error of Proposed Model; Paraboni- Barbaliscia Model and Hodge Model at different Reference Site

Ref Site	Proposed Model	ITU-R Paraboni-Barbaliscia Model	ITU-R Hodge Model
	RMS (%)	RMS (%)	RMS (%)
W3	10.4	20.8	31.5
TS	8.1	17.5	27.2
E4	6.0	12.1	28.8
N2	9.7	15.1	29.3
S2	8.6	13.8	28.1

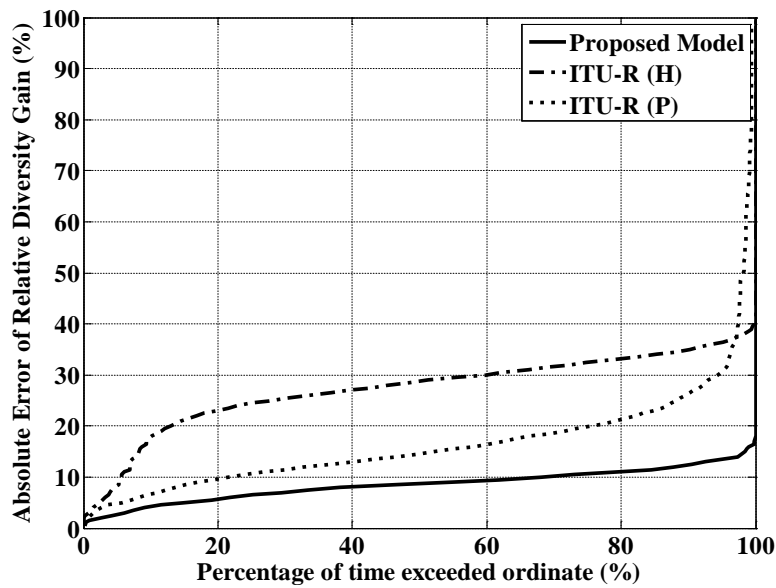


Figure 7. CDF of the Error of Relative Diversity Gain.

In order to verify the accuracy of the proposed model, the site diversity experimental results reported in [3] from Lae, Papua New Guinea is used for comparison. The main site of the experiment is located at 7°S, 147°E; and the remote site is 6.5 km away. Both sites used a 12.75 GHz beacon signal from OPTUS-B satellite at 160°E. The elevation angle of the receiving antennas is 72.8°.

Figure 8 shows the CDF of the diversity gain of the measured experimental result in Lae. From the calculation of (5), the RMS of the relative site diversity gain prediction error of the proposed model; Paraboni- Barbaliscia model and Hodge model are 2.4%, 8.6% and 18.6% respectively. This result is consistent with the Radar simulated results and verifies that the model is applicable for other geographical areas in the tropical region.

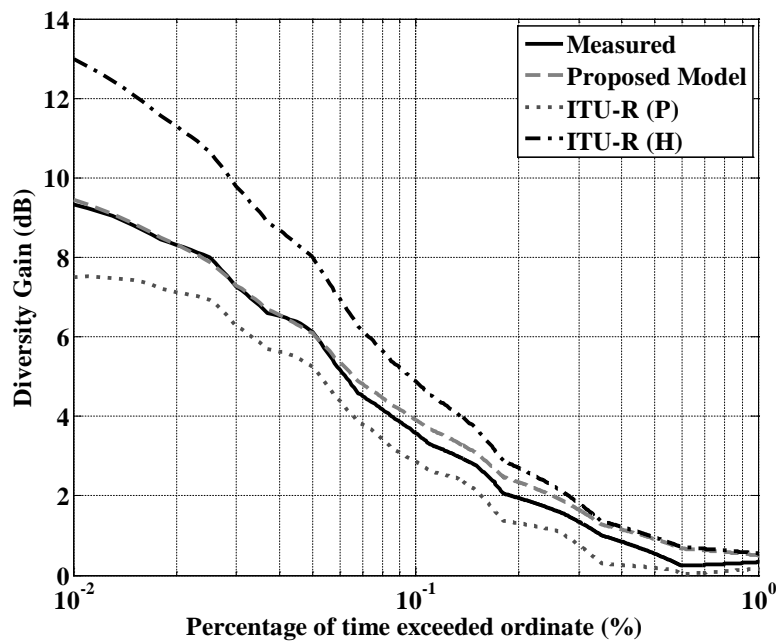


Figure 8. Comparison of CDF of Diversity Gain at Lae.

4.2. Effect of Monsoon Season on Diversity Gain

In our previous publication [15], it was concluded that monsoon wind is another factor that affects diversity gain since the wind can change the movement and shape of the rain clouds. Therefore, in this section, an investigation of rain events during different seasons is presented.

Table II. Seasonal months and the corresponding average wind speed and direction.

Monsoon Season	Months	Total Rain Amount (mm)	Average Wind Speed (m/s)	Wind Direction
NE	1,2,11,12	510.8	1.38	NE±34.5°
SW	5,6,7,8	936.0	0.57	SW±83.5°
Inter	3,4,9,10	377.2	0.30	SE±84.7°

Table II provides information about the monsoon months and their corresponding total rainfall amount, average surface wind speeds and wind directions. The wind speed and the total rainfall amount of the two main monsoons: North-East (NE) monsoon and South-West (SW) monsoon, are larger than that of the inter-monsoons. The wind direction during the NE monsoon is relatively constant whereas the wind direction during the SW monsoon varies significantly. This is because Singapore is close to the equator, only slightly north of the equator. Winds coming from the southern hemisphere change directions around the equator. Therefore, during the SW monsoon, the wind directions can change between the South-West direction and the South-East directions. Finally, the inter-monsoons consist of varied rainfall rates. During this season, wind directions are also varied.

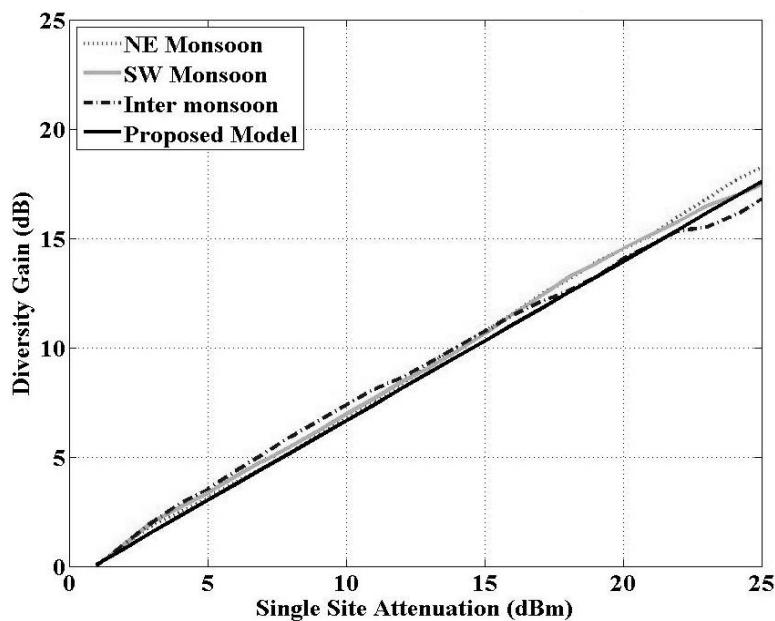


Figure 9. Effect of Monsoon Season on Diversity Gain.

Seasonal winds can be one of the factors that may affect the diversity gain. Therefore, in Figure 9, the diversity gain versus the single site attenuation is plotted for the 3 monsoon seasons given in Table 2. However, as shown in Figure 9, the effect of monsoon season on diversity gain is negligible. This may be due to the variation in wind direction and rain cell size for different rain events within the same monsoon season. Furthermore, the rain clouds are not blown across the island in the same direction as the wind direction, some

larger rain cells splits into two smaller rain cells due to the wind [15]. Therefore, the effect of wind counteracts each other and the diversity gain is similar to those of the yearly statistical result. Wind direction effects can be taken into account on an event by event basis and should not be taken into account for statistical modeling. This is only the case for Singapore’s climate and location; the prevailing seasonal wind may be one of the factors for site diversity gain prediction in other places with different climate and topography.

4.3. Performance of Triple-Site Diversity

Finally, we examine the use of a 3 diversity site system on the performance of diversity gain. Figure 10 shows the rainfall rate distribution of Singapore at 0.1% of the time and the 2-site joint attenuation at 0.1% of the time with reference sites at site *E3* and site *W3*. From the Figure 10(a), it is shown that the rainfall rate on the eastern part of the island is the lowest and maybe suitable as one of the station in a site diversity system. The same conclusion can be drawn for other percentages of the time. Based on the joint attenuation plot with reference site on the eastern part of Singapore, at *E3*, shown in Figure 10(b), the two sites with the lowest joint attenuation are sites *E3* and *SW13*. These two sites have a joint site attenuation of 2.0 dB at 0.1% of the time (diversity gain of 21.8 dB). Fig 9(c) shows the 2-sites joint attenuation distribution with the reference site on

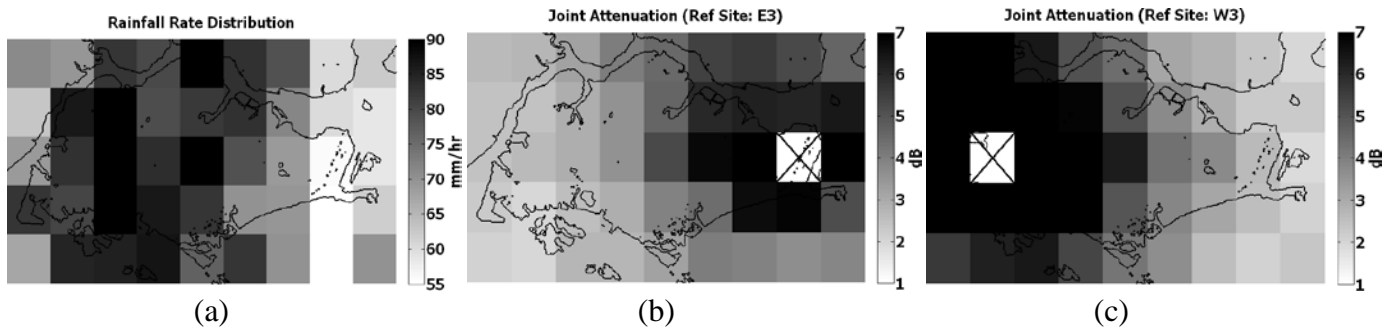


Figure 10. Rainfall Rate and 2-site Joint Attenuation Distribution of 45 Sites in Singapore. (a): Rainfall Rate; (b): Joint Attenuation with reference site *E3*; (c): Joint Attenuation with reference site *W3*.

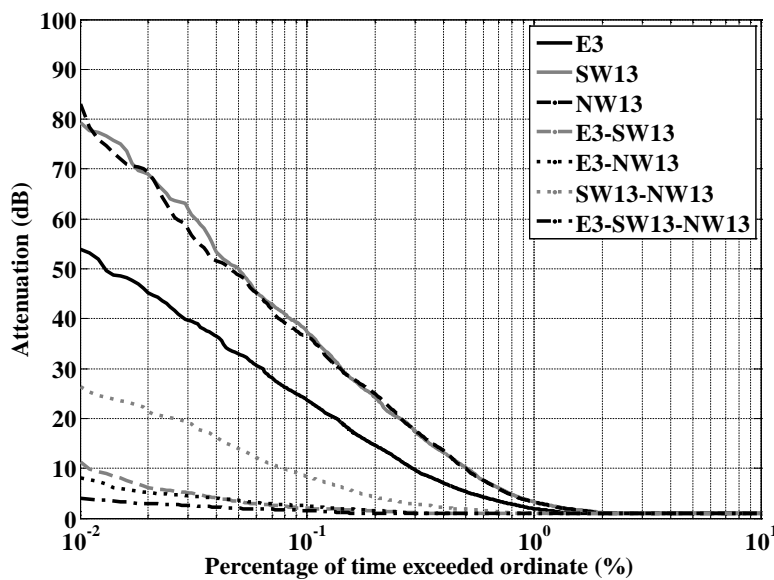


Figure 11. Performance of Triple Site Diversity ($F = 20\text{GHz}$, $\theta = 50^\circ$).

the western part of Singapore, at $W3$, the lowest joint attenuation is 3.0 dB at 0.1% of the time (diversity gain of 40.3 dB).

Figure 11 shows the CDFs of single site attenuation, 2-sites joint attenuation and 3-sites joint attenuation. By choosing the best 2-site diversity system at $E3$ and $SW13$, with the addition of one site at $NW13$ (based on our analysis, the best choice for the 3rd site) the joint site attenuation for the 3 sites is 1.5 dB at 0.1% of the time (diversity gain of 22.3 dB).

This shows that in the best case scenario, with an addition of a third site, there is only an improvement of 0.5 dB as compared to the two-site diversity system. Although a triple-site diversity system provides better protection against rain attenuation with a slight improvement in diversity gain, this comes at a price of an increase in system cost since a third site has to be set up. Therefore, as shown in Figure 11, with the proper selection of two diversity sites (with the best case scenario as presented above), the diversity gain is sufficient. An addition of a third site will increase the cost significantly and yield little returns in terms of diversity gain as already demonstrated for temperate areas [23].

5. CONCLUSIONS

Weather Radar data collected at Changi weather station in the year of 2003 and 16 months from May 2010 to August 2011 is used to construct the site diversity gain prediction model. A tropical site diversity gain prediction model is proposed and compared with the existing ITU-R Hodge model and the ITU-R Paraboni-Barbaliscia model. Unlike the ITU-R Hodge model which depends on five factors, the proposed model depends on only three of the five factors proposed by Hodge: the reference site attenuation, the site separation distance and the elevation angle. Our analysis shows that diversity gain has a linear relationship with the reference site attenuation and an exponential relationship with both the site separation distance and the elevation angle. It was shown that the performance of the proposed prediction model is improved as compared with ITU-R Hodge model and the ITU-R Paraboni-Barbaliscia model in tropical region of South-East Asia. The ITU-R Paraboni-Barbaliscia model performs better than the ITU-R Hodge model, but slightly worse than the proposed model and requires more information about the sites. The proposed model has the advantage of simplicity, ease of implementation and high in accuracy.

The seasonal statistical results show no significant effect on diversity gain from monsoon seasons for the Singapore climate. With different monsoon regimes, this tendency still needs to be demonstrated. Triple-site diversity gain is obviously better than two-site diversity gain. However the cost of setting up an additional station is high and counteracts the benefit of the diversity gain. It is shown that the proper selection of sites in a double site diversity system yields more benefits as compared to the implementation of a triple site diversity system.

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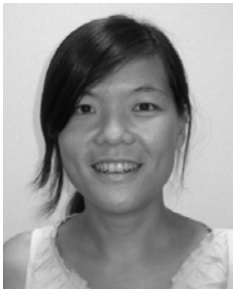
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AUTHORS' BIOGRAPHIES



Jun Xiang Yeo received the B.Eng. (Hons.) degrees in electrical and electronics engineering from the Nanyang Technological University, Singapore, in 2007. He is currently working toward the Ph.D. degree in the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. His research interests include the study of the effects of rain on performance of satellite communication and the mitigation technique to counteract rain fades.



Yee Hui Lee (S'96–M'02) received the B.Eng. (Hons.) and M.Eng. degrees in electrical and electronics engineering from the Nanyang Technological University, Singapore, in 1996 and 1998, respectively, and the Ph.D. degree from the University of York, York, U.K., in 2002.

She was the Assistant Professor with the School of Electrical and Electronic Engineering, Nanyang Technological University from 2002 to 2012. She is currently the Associate professor in Nanyang Technological University. Her interest is in channel characterization, rain propagation, antenna design, electromagnetic bandgap structures, and evolutionary techniques.



Jin Teong Ong received the B.Sc. (Eng.) degree from London University, London, U.K., the M.Sc. degree from University College, London, and the Ph.D. degree from Imperial College London, London.

He was with Cable & Wireless Worldwide PLC from 1971 to 1984. He was an Associate Professor with the School of Electrical and Electronic Engineering, Nanyang Technological (now Nanyang Technological University), Singapore, from 1984 to 2005, and an Adjunct Associate Professor from 2005 to 2008. He was the Head of the Division of Electronic Engineering from 1985 to 1991. He is currently the Director of research and technology of C2N Pte. Ltd.—a company set up to provide consultancy services in wireless and broadcasting systems. His research and consultancy interests are in antenna and propagation—in system aspects of satellite, terrestrial, and free-space optical systems including the effects of rain and atmosphere; planning of broadcast services; intelligent transportation system; EMC/I; and frequency spectrum management.

Dr. Ong is a member of the Institution of Engineering and Technology.