Performance of Site Diversity Investigated Through RADAR Derived Results

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***Abstract*—Site diversity is an effective rain attenuation mitigation technique, especially in the tropical region with high rainfall rate. The impact of different factors such as site separation distance, frequency, elevation angle, polarization angle, baseline orientation and wind direction is assessed. Results are compared to those reported in existing literature and also compared to the commonly used ITU-R site diversity prediction models. The effect of the wind direction on site diversity is also presented. It can be observed that diversity gain is highly dependent on the site separation distance, elevation angle and wind direction but independent of the frequency, baseline angle and polarization angle of the signal. This study is useful for the implementation of site diversity as a rain attenuation mitigation technique.**

***Index Terms*—Earth-satellite communication, site diversity.**

I. Introduction

As satellite transmissions at C band and Ku band become congested, it is a natural progression to use higher frequency bands for upcoming satellite services. Higher frequencies have wider bandwidth and channel capacity performance. However, higher frequencies also suffer from higher rain attenuation problems. This is especially true during monsoon seasons in the tropical region where heavy rainfall of above 100 mm/hr is often experienced. These heavy rainfalls can cause outage of signals and therefore, the 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 over 10 minutes in the Ka-band frequency of 20 GHz [1], [2]. In such situations, common mitigation techniques such as power control cannot be used to counteract the large signal fade. The dynamic range generally considered for power variation is about 10 dB [3]. One of the most effective methods to overcome such large signal fades due to rain attenuation is site diversity [4]. A site diverse satellite system consists of two or more spatially separated ground stations. The different sites provide less correlated propagation paths between the earth stations and the satellite. The concept of site diversity is based on the fact that short term large signal fades can affect one satellite link, but have less affect on another spatially separated satellite link. The effect of rain attenuation can be reduced or eliminated. The ground station with the higher received signal strength at any instant in time is always selected so as to significantly reduce the effect of rain attenuation.

Manuscript received August 06, 2010; revised March 06, 2011; accepted April 04, 2011. Date of publication August 04, 2011; date of current version October 05, 2011. This work was supported by the Defence Science and Technology Agency (DSTA).

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Digital Object Identifier 10.1109/TAP.2011.2163770

Most of the initial studies on site diversity are carried out in temperate regions [5]–[7]. Initial propagation studies for the Ku-band and/or higher frequency bands in the tropical region have started in the past few years. In 2001, some preliminary results on site diversity in the tropical country of Singapore were reported [8]. 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 gain can be obtained in the tropical region [3]. In 2010, the study of micro rain cell measurements was conducted in India [9]. They showed that site diversity can be effective for short distance site separation due to the existence of micro rain cells. However, there is little or no work done on the performance of site diversity with respect to separation distance, frequency, elevation angle, polarization angle, baseline orientation and wind direction in the tropical region.

In order to study the performance of site diverse systems, one of the most reliable and useful source of information, the weather RADAR data, is used. The weather RADAR data provides a true representation of the local climatology and topography of temporal and spatial rain field distributions. Studies have been done in temperate countries such as Italy and France, where the weather RADAR data is used to evaluate the performance of site diverse systems. Their results show that diversity gain is tightly linked to wind directions [10].

Models for predicting diversity gain has also been proposed based on the data from mainly temperate countries. The models can be classified in 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 [11], Matricciani [12] and Paraboni-Barbaliscia [13] models are well known physical prediction models of site diversity performance. The Hodge [14] 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 in the current ITU-R recommendation [15] for predicting site diversity gain. Since ITU-R model is the internationally accepted model, therefore, the analysis of results in the rest of this paper is based on a comparison with the ITU-R models (the Paraboni-Barbaliscia model and the Hodge model).

In this paper, the study of site diversity using full volumetric weather RADAR data in the tropical region is presented. Several factors, such as site separation distance, frequency, elevation angle, polarization angle, baseline angle and wind direction that may affect the site diversity gain will be examined individually. The results are compared to those reported in the literature and with the ITU-R site diversity prediction models.

TABLE I
SCANNING SCHEME OF AERIAL MODE

Tasks	Aerial_A	Aerial_B	Aerial_C
Elevation Angle(s)	0.1	1, 1.5	2, 3, 5, 7.5, 10, 15, 20
PRF (Hz)	300	1000	1000
Max Range (km)	480	120	120
Bin Width (m)	500	250	250
Scan Rate (deg/sec)	12	12	24
Output Bins	960	480	480
Start Range (km)	0.250	0.125	0.125

TABLE II
SCANNING SCHEME OF AIRPORT MODE

Tasks	Airport_A	Airport_B	Airport_C
Elevation Angle(s)	1.7	1, 15, 30	1, 1.5, 20, 40
PRF (Hz)	300	1000	1000
Max Range (km)	240	120	120
Bin Width (m)	250	250	250
Scan Rate (deg/sec)	12	24	24
Output Bins	960	480	480
Start Range (km)	0.250	0.125	0.125

Section II provides a description of the RADAR system and the full volumetric RADAR data used for this analysis. Section III describes the characteristics of the tropical climate in Singapore. Section IV deals with the calculation of path rain attenuation and site diversity gain. The calculated path attenuation and diversity gain is then analyzed to examine the effects of site separation distance, frequency, elevation angle, polarization angle, baseline angle, and wind direction in Section V. Conclusion are given in Section VI of the paper.

II. Description of RADAR System

The analysis of site diversity is based on the S-band RADAR data with an operating frequency of 2.71 GHz. Therefore, the understanding of the RADAR system and how the dataset is collected is important. 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 for the year 2003. The RADAR system is programmed to operate in two scanning modes, namely, the “Aerial Mode” and the “Airport Mode.” Each mode takes around 4 minutes for a full-volume scan. Both modes cover the entire land area of Singapore, parts of Malaysia to the north and Indonesia to the east, west and south. The normal operation of the RADAR system is in the “Aerial Mode.” The switching from “Aerial Mode” to “Airport Mode” is triggered when rainfall is detected within a 40×40 km^2 region centered at the Changi weather station. Once the RADAR system is switched to the “Airport Mode,” it will maintain in this mode for at least 20 minutes before switching back to the “Aerial Mode.”

In each of these scanning modes, the RADAR system implements full-volume scans in loops. The volume scans for both scanning modes consist of a sequence of tasks (Modes A, B and C) that are carried out in the order specified. Each task contains sweeps of scan around the region at a few elevation angles. Each elevation contains 360 rays of data corresponding to 360 azimuth angles. The spacing between two adjacent azimuth angels is 1°. The same set of tasks is repeated in each successive scan. The actual compositions of elevation angles for each task are different under the two different scanning modes. The specifications of the “Aerial Mode” and the “Airport Mode” are listed in Tables I and II respectively.

From Tables I and II, it is observed that, in the “Airport Mode”, the maximum scanned elevation angle is 40°, whereas in the “Aerial Mode,” the maximum scanned elevation angle is only 20°. This implies that, when there is a rain event on the island of Singapore, a full-volume scan of up to 40° is achieved. However, in the “Airport Mode” the maximum range of the RADAR is reduced from the original 480 km in “Aerial Mode” to half the distance of 240 km. This implies that during a rain event, the maximum scan range of the RADAR is reduced. In order to provide a higher resolution scan during rain events, the bin width is reduced from 500 m to 250 m.

III. Tropical Climate

One of the major factor affecting the effectiveness of site diversity as a rain attenuation mitigation technique is the climate. Singapore has a tropical climate. This implies that the rain rate in Singapore is generally high; where the rain rate exceeded for 0.01% of the average year is 100 mm/hr [16].

Singapore’s weather is traditionally classified into 4 periods according to the average prevailing wind direction:

a. the northeast monsoon season (December to March);
b. the inter-monsoon period (Late March to May);
c. the southwest monsoon season (June to September);
d. the inter-monsoon period (October to November).

The transitions between the monsoon seasons occur gradually over a 2 months period. During these transitions or inter-monsoon periods, the wind is usually light and tends to vary in direction from day to day.

During the northeast monsoon season, the wind generally blows from the north or northeast direction with the north direction being the main/stronger component. Similarly, during the southwest monsoon season, the wind blows from the south or southeast direction with the main/stronger component coming from the south [17]. The effect of wind direction on site diversity will be discussed in Section V.

Due to the rain shadow effect [17], there is significantly more rainfall on the west coast of the island than on the east coast. This phenomenon is caused by the Bukit Timah Hill, located near the centre of the Singapore main island. Therefore, the eastern side of Singapore is drier and slightly hotter than the western side. This can cause slight weather disparities from one side to the other side of the island. This accounts for a possible high diversity gain when one ground station is located on the east coast and another ground station on the west coast of the island.

Convective rain events are common over the tropical regions. Convective rain events are characterized by their short duration, high rainfall rate and small rain cell coverage area. These convective events are different from the stratiform rain events experienced in the temperate regions and the sub-tropical regions. Stratiform rain events are characterized by their long duration, low rainfall rate and large rain cell coverage area. In order to classify the type of rain events, the RADAR reflectivity threshold of 38 dBZ is used [18]. From the 315 rain events found in the RADAR data during the year 2003, more than 80% of the rain

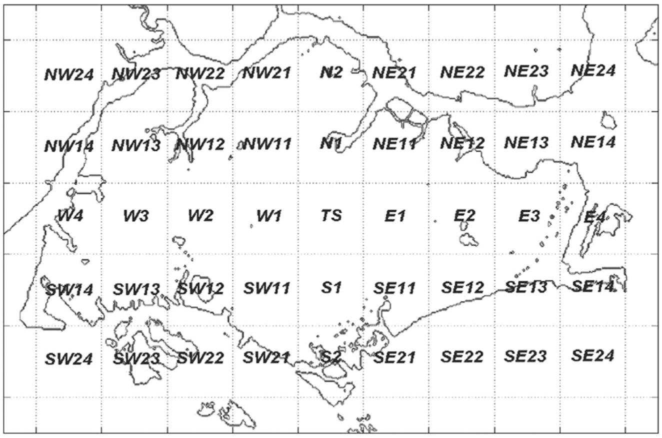

Fig. 1. Map of Singapore with the Partition of 45 Grids.

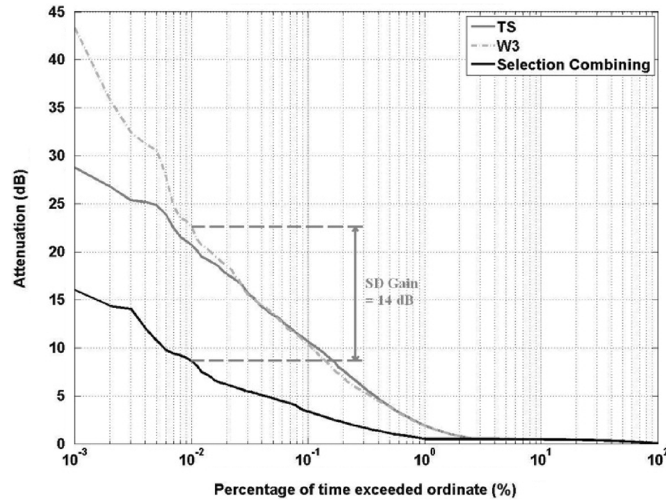

Fig. 2. CDF of Attenuation of Single Site *W3* and *TS* and Selection Combining of Two Sites.

events are convective. The average rain duration of these convective rain events are 10 minutes with rain cell size less than 15 km in size. Therefore, despite Singapore's small size, it is feasible to employ site diversity as a rain attenuation mitigation technique.

IV. Theoretical Formulation and Models

Simulations of the earth station to satellite links are carried out by assuming different earth station locations spread around the island of Singapore pointing towards the same geostationary satellite. The Wideband InterNetworking engineering test and Demonstration Satellite "KIZUNA" (WINDS) satellite located at 143°E with beacon frequency of 18.9 GHz and elevation angle of 44.5° is used because the beacon signal is being monitored.

As shown in Fig. 1, the overall map of Singapore is about 25 km by 45 km. In this study, the different locations of earth stations and their location as a diverse site in relations to factors such as rain cell size and wind direction will be examined.

Thomson is located at the center of the Singapore Island and is denoted as "*TS*." The grids in Fig. 1 are 5 km apart. The square "*E3*" for example, is located 15 km east of "*TS*" and is the location of weather RADAR system. "*W3*" is 15 km from "*TS*" and is the location of Nanyang Technological University, the university campus. In this paper, the sites "*TS*" and "*W3*" will be used as the reference sites for discussion and analysis of site diversity.

For ease of visualization and attenuation calculation, conical rain database in polar form is converted to 3-dimensional Cartesian system, constant altitude plan position indicator (CAPPI), through a 3-dimensional interpolation method [19]. The Marshall and Palmer Z-R relationship [20] in (1)

$$Z = 200R^{1.6} \tag{1}$$

is then used to convert the RADAR reflectivity values, Z, into rainfall rate at every Cartesian pixel. Finally, in order to calculate the rain attenuation along the slant path between the earth stations to the WINDS satellite, the path attenuation associated with each Cartesian pixel is calculated and then integrated over the length of the path in (2).

The slant path attenuation A is calculated through the numerically summation of

$$A = \sum_{i=0}^{n} kR_i^{\alpha} \cdot L_i \tag{2}$$

where $L = h_R/\sin(\theta)$ is the path length affected by rain, θ is the link elevation, h_R is the fixed yearly mean rain height, derived from ITU-R Rec. P.839-3 [21]. The coefficients of specific attenuation, k and α, can be obtained from the ITU-R Rec. P.838-3 [22], and is dependent on the link elevation angle, the radiowave frequency and polarization. In (2), R_i is the rainfall rate value at each Cartesian ith 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.

Using (2), all attenuation maps are calculated at 18.9 GHz and at an elevation angle of 44.5° unless otherwise stated. For analysis, different factors such as frequency, elevation angle and polarization angle can be changed accordingly. After calculating the path attenuation using (2), the site diversity gain at any two locations in the map can be determined in (3).

The gain G offered by a two-site diverse system, with separation D between the stations, can be calculated as [14]

$$G(D, A_S) = A_S(P) - A_j(D, P) \tag{3}$$

where $\mathrm{A_s}$ and $\mathrm{A_j}$ are the attenuation values of the cumulative distribution functions (CDF) (both for the same probability level P), relative to a single station and two sites diverse system (see Fig. 2). The CDF is calculated based on the whole year data of year 2003.

Fig. 2 shows the CDF of the path rain attenuation at sites *W3* and *TS* to the WINDS satellite. The CDF of rain attenuation after applying selection combining diversity for the two sites is also shown in Fig. 2. As can be seen, the diversity gain at 0.01% of the time is 14 dB with reference to *W3*; it reduces the joint attenuation to less than 10 dB. 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 eliminated.

The diversity gain simulated based on weather RADAR data is compared with the two ITU-R models, Paraboni-Barbaliscia

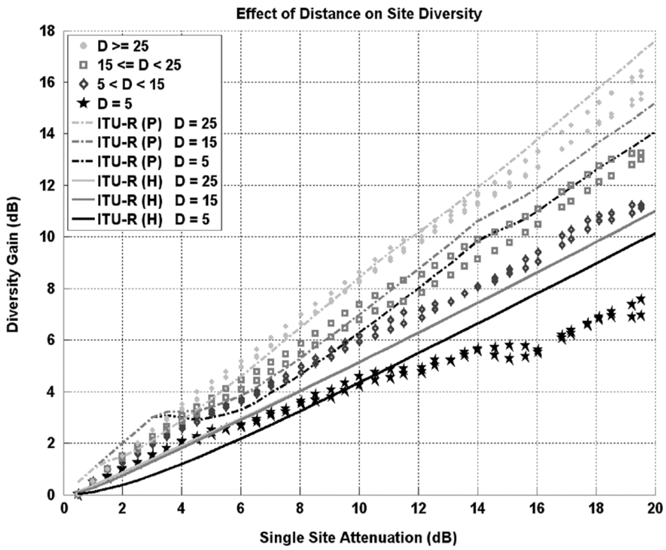

Fig. 3. Effect of Site Separation ($\mathrm{F} = 18.9$ GHz; $\theta = 44.5°$; $\mathrm{pol} = \mathrm{V}$).

model and Hodge model. Paraboni-Barbaliscia model hypothesize that the single site and joint probability of the rain attenuation have log-normal behaviors. With the physical measured CDFs of rainfall rate and single site rain attenuation, the site diversity gain can be calculated. Hodge model specifies that the site diversity gain is dependent on a number of factors; site separation distance, d; frequency, f; elevation angle, θ; and baseline angle, Ψ. In this paper, each one of these factors and their relationship with diversity gain will be examined in the following section.

V. Results and Discussion

The separation distance between the diverse sites is the major factor that influences the performance of site diversity as a mitigation technique. As discussed in Section IV, the path attenuation of the earth-satellite link depends on the baseline angle, frequency, the link elevation angle and polarization. Since these factors affect the path attenuation, they will also vary the diversity gain. Therefore in this section, the effect of all these factors on a two site diverse system will be analyzed in detail. Besides these factors, the effect of wind direction will also be investigated.

A. Gain Dependence on the Site Separation Distance

Site separation distance, D, is the major factor that affects the amount of diversity gain for any two site diverse systems. Fig. 3 shows the diversity gain against the single site attenuation with reference to site *W3*. The effect of different site separation distance, D, on the diversity gain is plotted as scatter plots with other factors kept $\mathrm{constant\ at\ frequency} = 18.9$ GHz, $\mathrm{elevation\ angle} = 44.5°$, vertical polarization and $\mathrm{baseline\ angle} = 0°$. For comparison and analysis purposes, the effects of distance for 5 km, 10 km, 15 km and 25 km are plotted in solid lines for ITU-R Hodge model, ITU-R (H), and dotted line for ITU-R Paraboni-Barbaliscia, ITU-R (P) model in Fig. 3.

As can be seen, all solid lines are very close to each other. This indicates that the Hodge model assumes that the site separation distance has negligible effect on diversity gain. This behavior is also mentioned by Panagopoulos [23]. In the formulas used for calculation in the Hodge model, the dependency of sites separation distance on diversity gain decreases exponentially as the distance increases.

This low dependency on distance is due to the database used for the derivation of the Hodge model. The database used consists of mainly data collected in temperate countries. The type of rain experienced in the temperate region is mainly stratiform type rain and therefore, have low rain rate over a large coverage area. Hence, the site separation distance between two sites of up to 20 km does not produce significant difference in diversity gain.

Unlike temperate countries, the tropical island of Singapore experiences mostly convective type rain events. This implies that most of the rain cell sizes are less than 15 km. Therefore, diverse sites with separation distance >15 km are generally not located within the same rain cell. In most of the rain events, the diverse sites are not within the same rain cell, therefore the likelihood of simultaneous rain at both sites becomes small. This result in a high diversity gain as the separation distance, D, increases as shown by the scatter plots in Fig. 3. From Fig. 3, it can be seen that the Hodge model is more suited for temperate and sub-tropical region, therefore, tends to underestimate the diversity gain for the tropical region. A separation distance of $\mathrm{D} > 15$ km results in a higher diversity gain as compared to those predicted by the Hodge model.

The Hodge model can predict well for the separation distance less than 15 km (blue and pink scatter dots). However, for separation distance equal or less than 5 km, the Hodge model can only predict well for single site attenuation less than 10 dB. Beyond the attenuation of 10 dB, the Hodge model tends to overestimate the diversity gain. This is because the attenuation larger than 10 dB corresponds to about 50 mm/hr rainfall rate which occurs for about 0.1% of the yearly time. The rain cell size of such a high rainfall rate is usually larger than 5 km. Therefore the diverse stations are located within the same rain cell and a much smaller diversity gain is obtained.

It can be noticed that there is no significant increment in diversity gain for separation distance larger than 25 km. This is because of the decreasing likelihood of simultaneous rainfall at both diverse sites for large separation distances of $\mathrm{D} > 15$ km. Therefore, the diversity gain at large site separations is saturated. This is consistent with the theoretical optimum sites separation range between 10 and 30 km as reported in [4].

The ITU-R Paraboni-Barbaliscia model uses the physical data of rainfall rate and single site rain attenuation to predict site diversity gain. Therefore, it is found to predict the diversity gain well since the measured RADAR data is used for the calculation of diversity gain. This is especially so for the site separation distance larger than 15 km. However, the threshold of the formula in the Paraboni-Barbaliscia model is based on the data obtained in Europe. Thus, it tends to overestimate the diversity gain for the tropical region. As seen from Fig. 3, the Paraboni-Barbaliscia model overestimates the diversity gain for a separation distance of less than 15 km. For separation distance

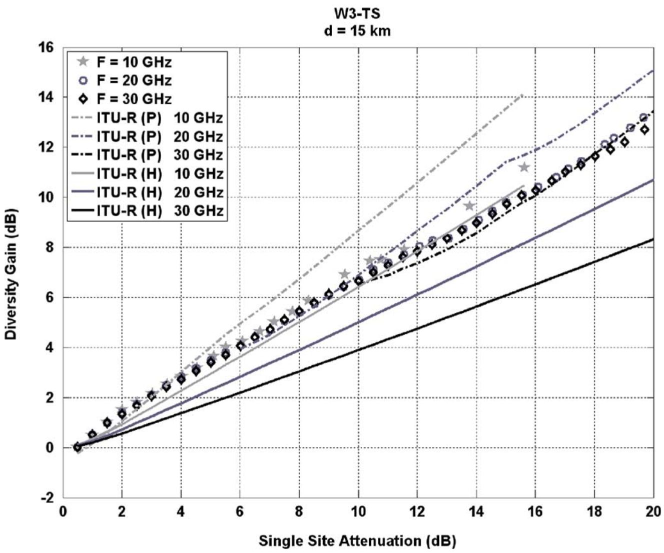

Fig. 4. Effect of Frequency ($\mathrm{Distance} = 15$ km; $\theta = 44.5°$; $\mathrm{pol} = \mathrm{V}$).

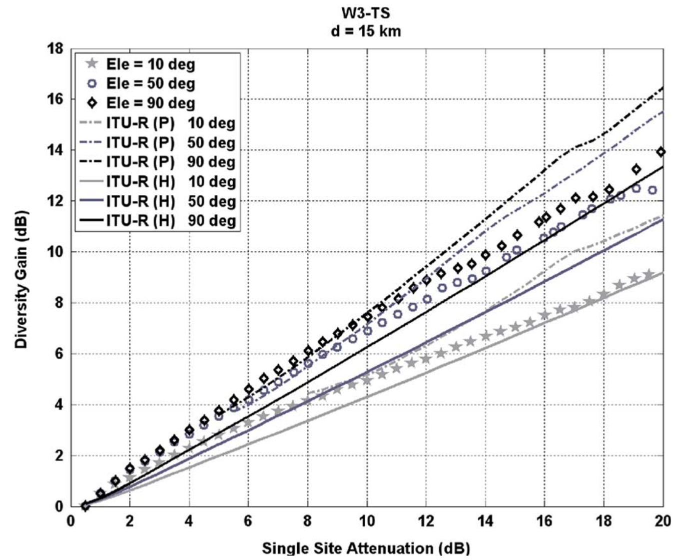

Fig. 5. Effect of Elevation Angle ($\mathrm{F} = 18.9$ GHz; $\mathrm{Distance} = 15$ km; $\mathrm{pol} = \mathrm{V}$).

of greater than 15 km and single site attenuation less than 10 dB, this model fits the Singapore data well. This is because any two sites with a separation distance of above 15 km is usually out of the coverage of a single convective rain cell, but is likely to be within the same stratiform rain cell (similar to most rain events in Europe). Therefore, the Paraboni-Barbaliscia model can predict the diversity gain in both temperate and tropical regions well. However, in temperate climate, high attenuation of above 10 dB due to rain rate greater than 50 mm/hr is seldom, therefore, as seen in Fig. 3, as attenuation increases, the Paraboni-Barbaliscia model deviates from the Singapore data.

B. Gain Dependence on the Operating Frequency

Fig. 4 shows the diversity gain against the single site attenuation with reference to site *W3* at the Ku and Ka-band frequencies from 10 GHz to 30 GHz. For fair comparison, the distance, elevation angle, polarization and baseline angle are kept constant at $\mathrm{D} = 15$ km, $\mathrm{elevation\ angle} = 44.5°$, vertical polarization, $\mathrm{baseline\ angle} = 0°$. It is interesting to note that the diversity gain from the simulation is independent of frequency of transmission. This indicates that, although the frequency is different, diversity gain remains the same for the same single site attenuation. In the study done by Goldhirsh [24], a similar conclusion was drawn. His results show that carrier frequency appears to play a minimal role in establishing diversity gain statistics.

When compared to the two ITU-R models, as shown in Fig. 4, the predicted diversity gain of both ITU-R models varies significantly with frequency. As the frequency increases, the diversity gain decreases. The Hodge model tends to underestimate the diversity gain in the tropical region but predicts well the diversity gain for low frequency signal at 10 GHz. This is because the Hodge model is based on measurements performed mainly between 11 GHz and 13.6 GHz within the Ku band and not based on measurements performed at Ka band frequencies [25]. Therefore, the extrapolation of the Hodge model for higher frequencies is not accurate and should not be used. On the other hand, the Paraboni-Barbaliscia model tends to overestimate the diversity gain in tropical region but predicts well the diversity gain for high frequency signal at 30 GHz. This is because the Paraboni-Barbaliscia model is a physical model that is constructed to predict the diversity gain of the satellite links for frequencies of Ka-band and above [13].

The diversity gain is independent of frequency for a given fix single site attenuation. However, for a rain event, the attenuation suffered by a Ku band link is smaller than that of a Ka band link. Therefore, in that rain event, the diversity gain for the Ku band link is smaller than that of the Ka band link.

C. Gain Dependence on the Elevation Angle

Diversity gain increases as the elevation angle of the propagation path increases. Fig. 5 shows the diversity gain against the single site attenuation with reference to site *W3* at different elevation angles. For ease of analysis, the frequency, distance and polarization and baseline angle are kept constant at $\mathrm{D} = 15$ km, $\mathrm{f} = 18.9$ GHz, vertical polarization, $\mathrm{baseline\ angle} = 0°$.

As shown in Fig. 5, the diversity gain of both ITU-R models increases with the elevation angle of the slant path. This is because, as the elevation angle increases, the slant path length that suffers from rain attenuation decreases and two diverse sites becomes less correlated with one another. When the slant paths become less correlated, the diversity gain is expected to increase. The simulation results show a similar trend, where there is an increase in diversity gain with an increase in elevation angle. However the simulation results show that the diversity gain decreases drastically for elevation angles less than 30°. This is because the propagation path for lower elevation angles is long; therefore, the likelihood of both paths passing through the same rain cell becomes high. This is especially true for the elevation angle of 10° where the projected path length is approximately 28 km. Due to the long path length, any sites along the east-west line (geostationary satellite) less than 28 km away is very likely to be affected by the same rain cell. This implies that for low elevation angles, due to the long path length, the correlation of rain attenuation between two sites are likely to be high and therefore results in a significantly lower diversity gain.

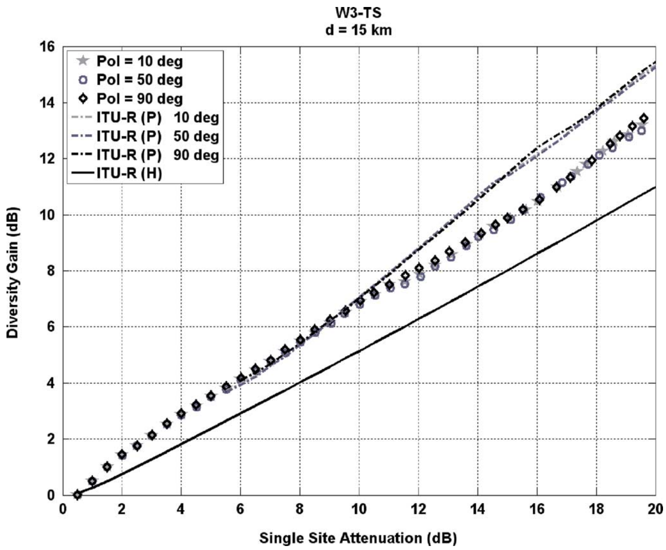

Fig. 6. Effect of Polarization (F $= 18.9$ GHz; $\theta = 44.5^{\circ}$; Distance $= 15$ km).

At high elevation angles, the simulation results although follow the same trend as the Hodge model, is almost always higher in diversity gain. This is because the tropical climate consists of mostly convective rain events and these convective rain events have smaller rain cell size and high attenuation (high rain rates). Therefore, the simulated diversity gain is almost always higher than the Hodge model. As explained before, due to the long path length at low elevation angle, there is a drastic drop in diversity gain from 50° to 10° for the simulated results. However, this trend is not observed in the Hodge model. Based on the formula in the Hodge model, the diversity gain is found to decrease proportionately with the decrease in elevation angle. The Hodge model tends to underestimate the diversity gain since it was derived from Ku-band data. The Paraboni-Barbaliscia model follows the same trend as the simulation results. This model always follows the same trend as the simulation results since the model is based on the regressive fitting to the simulation results. However, as observed in previous results (Fig. 3), this model estimates the diversity gain well for a single site attenuation of up to 10 dB since this model was developed for Ka-band applications in the temperate region.

D. Gain Dependence on the Polarization

Fig. 6 shows the diversity gain against the single site attenuation with reference to site W3 at different polarization angles. Similarly, all other parameters are kept constant with the frequency of 18.9 GHz, elevation angle of 44.5°, distance of 15 km and baseline angle of 0°. The results shows polarization has negligible effect on site diversity gain. This agrees well with both ITU-R models. Thus, a system designer could disregard the impact of polarization angle in estimating the system performance through prediction methods. Again, as explained before, due to the convective rain events experienced in the tropical region and the simulation done for Ka-band, the diversity gain simulated is higher than those obtained from the Hodge model. Again, similar to previous findings, the diversity gain from the Paraboni-Barbaliscia model estimates the simulation results well up to 10 dB of single site attenuation and then overestimates.

E. Gain Dependence on the Baseline Orientation

The baseline angle is the angle made by the azimuth of the propagation path with respect to the baseline between sites. Since the latitude of Singapore is very low (less than 1.5°) and if the satellite of interest is a Geo-stationary satellite, the azimuth angle is almost always around 90°, which is also known as the west-east direction. This therefore implies that a baseline angle of 0° is in the west-east direction while a baseline angle of 90° is in the north-south direction.

Fig. 7 shows the site diversity gain of 45 sites around Singapore with reference to site *TS* (cross in Fig. 7), provided that the frequency, elevation angle and polarization angle are kept constant at 18 GHz, 44.5°, and 90° respectively. The diversity gain figure from Paraboni-Barbaliscia model is similar to that of the simulation results as shown in Fig. 7. The only different is the diversity gain for the separation distance less than 15 km is higher than the simulation result. This is because this model is based on fitting of the simulation result as explained before.

As seen from the Hodge model in Fig. 7, the diversity gain increases as baseline angle increase. This is because, the satellite path to a geo-stationary satellite is always in the east- west direction (forming a horizontal path), as the baseline angle increases, the north south distance between the two parallel paths will increase. With the increase in distance of the two paths, diversity gain increases. However, from the simulated result in Fig. 7, it can be seen that in reality, the gain increase with site separation distance, as analyzed in part A, Fig. 3. There is also little or no correlation between baseline angle and diversity gain from the simulation result. The lack of correlation between the baseline angle and the diversity gain obtained from the simulation results as compared to the Hodge model can be explained by the rain cell motion and wind direction as reported in [10]. Therefore, in the part F of this paper, the effects of wind direction and rain cell motion will be examined in detail.

F. Gain Dependence on the Wind Direction

By visual inspection of RADAR constant altitude plan position indicator (CAPPI), the rain cells usually either forms over the Malaysia peninsular or the South China Sea. The rain cells are then blown across the Singapore inland from either the north coast from the Malaysia peninsular during the northeast monsoon or the south coast from the South China Sea during the southwest monsoon. These prevailing winds sometimes collide with the sea breeze along the coast and form thunderstorm rain cells [17].

Analysis of the RADAR data statistics suggest that almost half of the rain cells that start off with a cell size larger than 10 km tend to elongate perpendicular to the direction of wind. The rest of the rain cells propagate in the direction of wind.

Fig. 8 shows the CAPPI images on 23 January 2003 during the northeast monsoon season. The wind is blowing from the northwest west direction and the rain cell propagates in the same direction as the wind. This is the most common type of rain event experienced in Singapore. Over 85% of the rain cells in the year 2003 moves in the same direction as the prevailing wind.

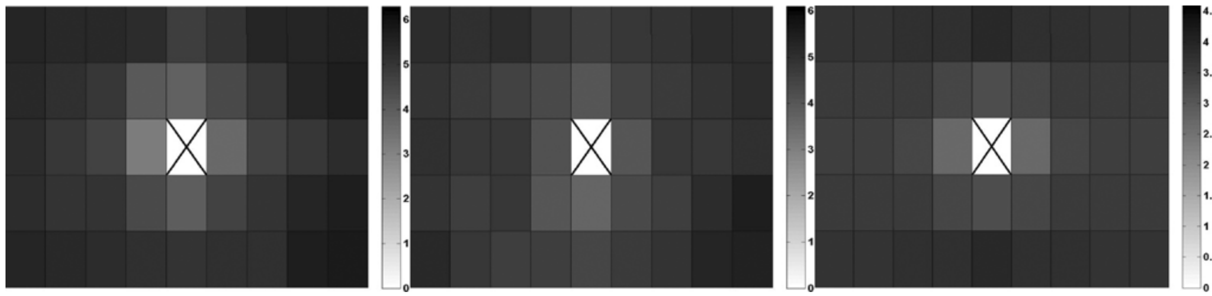

Fig. 7. Site Diversity Gain around Singapore (Left: 1 year simulated result; Middle: Paraboni-Barbaliscia model predicted result; Right: Hodge model predicted result).

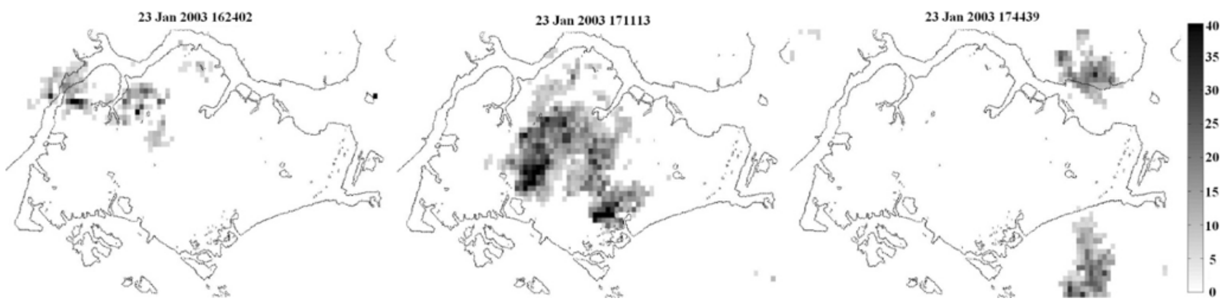

Fig. 8. CAPPI images at 500 m a.s.l. on 23 Jan. 2003 (16:24–17:44)—Rain cell moves in the direction of the wind.

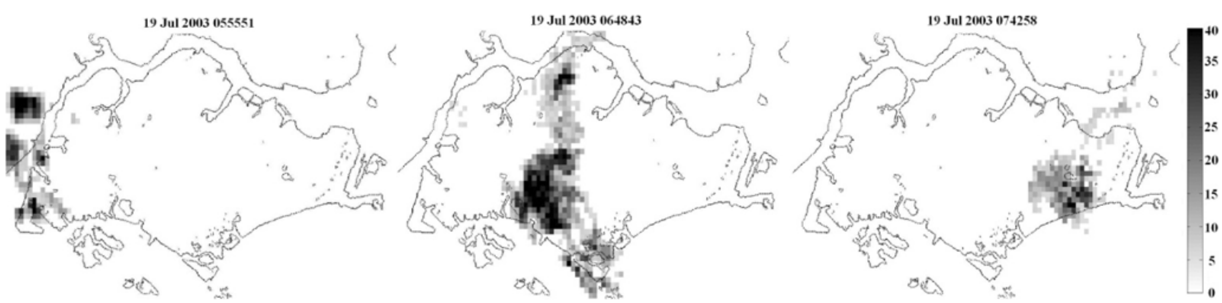

Fig. 9. CAPPI images at 500 m a.s.l. on 19 Jul. 2003 (05:55–07:42)—Rain cell elongated in the direction of the wind.

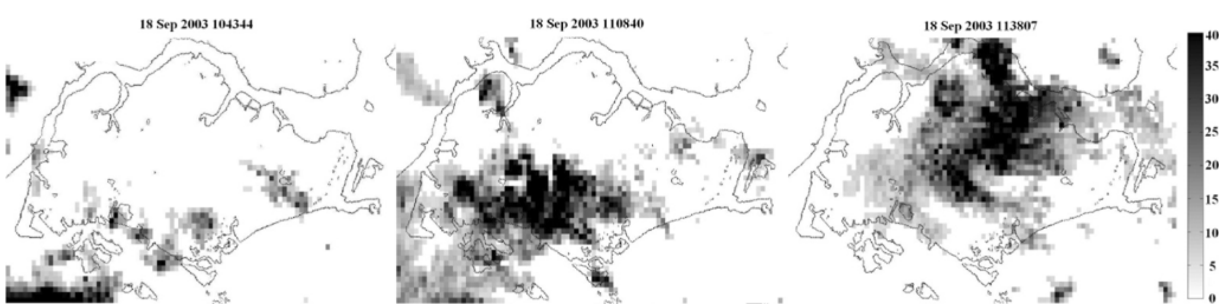

Fig. 10. CAPPI images at 500 m a.s.l. on 18 Sep. 2003(10:43–11:38)—Sumatra squall.

Since the rain cell moves in the direction of the wind, a higher diversity gain will be obtained if the two stations are located perpendicular to the direction of the surface wind, in this case, one station in the south western part of Singapore and another in the north eastern part of Singapore.

Fig. 9 shows the CAPPI images on 19 July 2003 during the southwest monsoon season. This rain event is a result of the collision between the prevailing winds and the coastal winds as explained earlier. If the rain cell is large, greater than 10 km, as shown in Fig. 9, the rain cell stretches perpendicular to the wind direction. Once this happens, the diversity gain can be maximized if the two stations are located in parallel to the direction of the surface wind. In the case in Fig. 9, high diversity gain with a zero joint attenuation can be achieved if the site diverse stations are located one in the eastern part and another in the western part of Singapore. This is because; the wind is blowing from west to east, bringing the rain clouds together with it. Therefore, the rain will not occur simultaneously on both the east and west coast of the island.

Fig. 10 shows the CAPPI images on 18 September 2003 during the southwest monsoon. The rain cell covers almost the whole Singapore. This is known as Sumatra Squall. Only

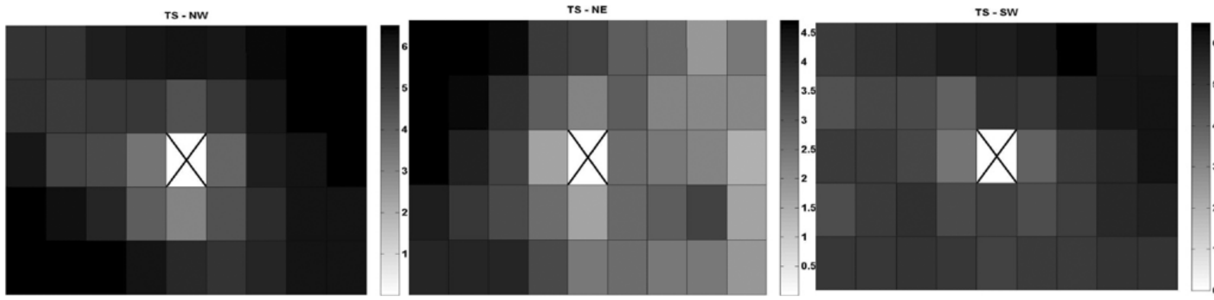

Fig. 11. Site Diversity gain of the rain events with different wind direction—Rain cell moves in the direction of the wind (Left: North-West; Middle: North-East; Right: South-West).

10 rain events in the year 2003 belongs to this type of rain. A Sumatra Squall is an organized thunderstorm line that develops over the island of Sumatra, Indonesia or the Straits of Malacca, often overnight, and then moves eastward towards Singapore arriving in Singapore in the early hours in the morning [17]. The rain cells move and behave collectively and can have a long lifespan. However, as the rain cell moves towards the eastern side of Singapore, the rainfall generally decreases. In the meantime, the rainfall on the western side also decreases. Therefore, during the Sumatra Squall, site diversity is low for all locations around Singapore regardless of distance or baseline angle. This is because the large rain cells will cause rain attenuation to all site diverse paths across the island to the same extent.

Rain events in Singapore can generally be classified into three types based on the rain cell size and rain cell motion. The rain cell type most commonly observed moves in the direction of the surface wind. For such rain cells, a baseline orientation perpendicular to the wind direction will result in maximum diversity gain. If the rain cell size is larger than 10 km and stretches perpendicular to the wind direction, an optimum diversity gain can be obtained with the baseline orientation parallel to the wind direction. For the case of Sumatra squall, since the rain cell is almost covering the whole Singapore Island, very little diversity gain can be obtained. With the rain cell blown from the south-western part of Singapore, the station in north-eastern part will suffer less attenuation from the rain event and hence can be set as a diverse station.

As reported in [10], the diversity gain is related to the wind direction only if the rain cells stretch orthogonally to the wind direction. As shown in Figs. 8 and 10, there exist rain events where the rain cells move with the wind direction or spreads over a large area (Sumatra Squalls). Therefore, diversity gain is not only related to the wind direction, but also the rain cell structure.

In order to study the effect of wind on diversity gain, all rain events with rain cells moving in the direction of the wind are separated based on the wind directions (North-West, North-East, South-West and South-East). The diversity gains around Singapore with the reference site at *TS* (cross in Fig. 11) are then plotted in Fig. 11. Since the one year RADAR data has too few data with wind direction from south-east that passes through site *TS*, therefore it is not meaningful to show the diversity gain map for the south-east winds.

As shown in Fig. 11, if the wind is blowing from the north-west direction, a large diversity gain can be obtained with the diverse site set at north-eastern or south-western part of Singapore. If the wind is blowing from north-east direction, north-western part of Singapore has higher diversity gain. However, if the wind is blowing from south-west direction, the rain cells break up or die off and seldom reach the north-eastern part of Singapore, therefore the diversity gain at north-eastern part is higher than north-western and south eastern part of Singapore.

Since the site diversity has little or no correlation with baseline angle but is dependent with the wind direction, it would be possible, in principle, to conceive a site diversity gain prediction model (specific to Singapore) using the wind direction as an additional variable rather than the baseline angle.

VI. Conclusion

Weather RADAR data collected at Changi weather station in the year of 2003 is used to evaluate the effect of several factors that may affect the performance of Satellite-Earth site diversity system. Unlike both the ITU-R models (Hodge model and Paraboni-Barbaliscia model), the analyzed results show that site diversity gain is much more sensitive to the separation distance. The Paraboni-Barbaliscia model predicts the simulation results well up to 10 dB and then overestimates the diversity gain for distance larger than 15 km since this model was constructed for Ka-band applications based on a database from the temperate region. The Hodge model tends to underestimates the diversity gain for distances larger than 15 km since the model was developed from Ku-band data collected mainly in the temperate region. From simulation results, the diversity gain tends to saturate at the large separation distance of 25 km.

The site diversity gain is independent of frequency and polarization angle, provided the reference site attenuation and other factors are kept constant. The site diversity gain will increase with elevation angle of the earth-satellite link increases. However, the gain does not increase linearly as suggested by the Hodge model. The Hodge model always underestimates the diversity gain for different elevation angle and the Paraboni-Barbaliscia model follows the same trend as the simulation results. For elevation angles larger than 30°, the Paraboni-Barbaliscia model estimates the simulation results well up to 10 dB of single site attenuation and then overestimates. Simulated results show that diversity gain decreases drastically for elevation angles less than 30° due to the large path length and the high possibility of the diverse paths passing through the same rain cells.

The effect of baseline angle on the diversity gain is found to be negligible. The system gain is tightly linked to the direction of wind and rain cell motion. If the rain cell moves in the direction of the wind, higher diversity gain can be obtained for the baseline angle perpendicular to the wind direction. More than 85% of the rain cell moves in this manner. If the rain cells stretch orthogonally to the surface wind direction, the diversity gain can be maximized if the baseline angle of the stations is parallel to the surface wind direction. No large system gain can be found in Sumatra squall due to its huge rain cell size. It can be concluded that diversity gain is not only related to wind direction but also the rain cell structure.

ACKNOWLEDGMENT

The authors are grateful to anonymous reviewers for their constructive comments and suggestions for the paper.

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