Analysis of Rainfall Distribution in Malaysia through the Employment of Hydro-Estimator Data

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ABSTRACT

Rain rate influenced by atmospheric factors is related to rainfall patterns affected by climate change. Attenuation and signal losses due to rain are crucial constraints in communication systems such as 5G, microwave radio links, and communication satellite systems. These communication systems have been deteriorated due to signal fading and distortion when exposed to rain. Signal fading by hydrometeor particles in the atmosphere may occur during wireless signal transmissions at frequencies higher than 10 GHz. In this paper, Hydro-Estimator data for the Peninsular Malaysia, Sabah and Sarawak regions from 2011 to 2022 were extracted to determine the rain rate distribution, which is a crucial parameter for simulating and analyzing rain fade. Climate change affects rainfall distribution when signal transmission with higher frequency carries more data, thus resulting in a higher chance of signal loss and degradation. Long-term forecasts of the signal performance in 5G systems and high-frequency radio link frequencies can be developed by analyzing the effects of climate change based on the rainfall rate and the rain fade distribution.

Keywords-Hydro-Estimator; ITU-R 530; data transmission; wireless communication; NESDIS; NOAA; mmWave link

I. INTRODUCTION

Greenhouse effect denotes the warming caused by greenhouse gases that retain heat in the Earth's atmosphere [1-3]. Although the atmosphere naturally contains some greenhouse gasses, human activity has increased the concentration of these gasses, especially since the industrial revolution. Deforestation, energy generation, and the combustion of fossil fuels are the main causes of Carbon Dioxide (CO_2) emissions [4-6]. Increasing emissions of greenhouse gases, especially CO_2 from burning fossil fuels, such as coal, oil, and natural gasses, have been recognized as the main contributors to man-made climate change, which in turn changes temperature and weather patterns. Changes in rainfall patterns are an aspect that causes differences in rain rates, intensities, and frequencies, with some places facing drought conditions and others dealing with more frequent and intense rainfall events. Electromagnetic waves colliding with rainfall in the atmosphere cause signals to weaken, impacting radio waves utilized in wireless communication, including 5G networks [7, 8]. This effect is known as rain fade or rain attenuation. 5G networks are more vulnerable to rain fade because they operate at higher frequency bands specifically millimeter-wave frequencies that exceed 24 GHz [9]. Changes in rainfall patterns driven by climate change make rain fade effects on 5G signals more severe, causing service interruptions or degradation during periods of intense rainfall.

Technology for wireless communication has evolved into an essential component of everyday life. Additional information is sent and received in more complex multimedia formats as technology develops, including pictures, movies, and intricate mobile applications [10–16], which indicate increased bandwidth and faster data transmission. Wireless backhaul is heavily utilized to meet the demands for a more adaptable wireless data service. The millimeter wave range, which spans frequencies from 30 to 300 GHz, is thought to be the ideal region for achieving large channel bandwidths while reducing interference, allowing high-speed data transfer, and enhancing propagation characteristics by increasing the uniformity of the signal distribution [17]. Implementing 5G, however, poses great difficulties because higher frequency signals are predicted to suffer significant signal losses due to absorption and scattering effects brought on by the presence of hydrometeor particles in the atmosphere, such as rain, clouds, fog, and sleet [18]. Rain fade is the major and most unpredictable factor in these signal losses. Occurring rain events can move quickly to different locations and can last anywhere between a few minutes and several hours, which renders them highly dynamic in both space and time. It can be very difficult to measure the rain rate during typical heavy rainfall events, which can move at speeds of up to 8 meters per second [19].

The National Environmental Satellite Data and Information Service (NESDIS) and the National Oceanic and Atmospheric Administration (NOAA) in the USA currently run the Hydro-Estimator, a product of meteorological data that includes information on rainfall rate. Rain gauge, rain radar, and weather satellite data are combined and solidified to produce rain rate statistics on a worldwide scale [20].

II. PREVIOUS WORK

In satellite communications, the effects of atmospheric fading, particularly rain attenuation, which is considered the dominant factor, severely degrade the system performance for the Ka-band satellite channel. Moreover, tropical regions that encounter severe weather, heavy rainfall, and increased precipitation intensity have a notably greater influence on radio links operating at frequencies higher than 7 GHz [21]. The rain trend is also predicted to change over time due to the primary threat of global climate change, and thus a significant impact on the rain fade is brpought. Authors in [22], utilizing the industry-standard ITU-R 838 model, rain gauges, radars, and weather satellites, were able to estimate rainfall rate in mm/hr and convert the rainfall rate to rain attenuation or fade in dB. According to the International Telecommunication Union (ITU) P. 837 and 530 recommendations, plotting annual rain attenuation or rain fade distribution typically requires 1 min of integration time of annual rain rate distribution [23]. However, based on data gathered by the ITU from various regions, the methodological approach for predicting rain attenuation on terrestrial radio links does not work effectively in tropical climates [24]. Various meteorological measuring techniques obtained different temporal sampling and spatial coverage, each having specific parameters for rainfall research. Rain gauges generate highly temporally resolved localized data that can be used for in-depth analysis of short-term events [25]. Rain radar devices are perfect for comprehending rainfall patterns on larger scales since this method offers regular updates and broader coverage spanning hundreds of kilometers [26]. Weather satellites are useful for researching large-scale weather trends since this method offers worldwide observations, albeit with a slightly lower temporal resolution [27]. Studies of broad rainfall trends can benefit from the modest temporal resolution and global coverage provided by the Hydro-Estimator [28]. Table II shows the comparison of various meteorological measurement methods. The method of choice is determined by the needs of the research, taking into consideration temporal and spatial resolution. To enhance accuracy, this rain measurement method integrates the measurement sources with numerical weather prediction models, developed in [29]. The sampling period of the Hydro-Estimator is 1 hr for global coverage. However, the sampling period can be converted to 1 min integration period to predict rain rate and, in turn, rain fade, using the regression technique provided by the ITU.

TABLE I. COMPARISON OF METEOROLOGICAL MEASUREMENT METHODS

Meteorological measurement methods	Parameters	
	Spatial coverage	Temporal sampling time
Rain gauge	Hundreds of m to a few km	1 min to 1 hr
Rain radar	Hundreds of km	5 to 15 min
Weather satellite	Continent or Globally	30 min to 1 hr
Hydro-Estimator	Globally	1 hr

Table III portrays the comparison of the previous research works. The comparison enables researchers to analyze the method applied, the spatial and temporal extents explored, and the weather climate change analysis.

TABLE II. COMPARISON OF PREVIOUS WORKS

Work	Method	Spatial area coverage	Integration time	Climate Change analysis
[30]	Weather satellite	~ 3 to ~ 28 km^2	30 min - 1 hr	No
[31]	Rain gauge	~ 3 km^2	1 min - 1 hr	No
[32]	CMORPH-CRT and rain gauge	~ 8 km^2 (rain gauge)	1 hr	No
[33]	Hydro-Estimator	Globally	1 hr	Yes
This work	Hydro-Estimator	Globally	1 min - 1 hr	Yes

Authors in [30] proposed a novel solution model for mitigating rain attenuation in Earth-space communication links operating above 10 GHz frequencies. The idea of rain rate gain, which is the difference between real-time rain rates with and without time delay, was first presented in that study. The findings of the study, which have been confirmed by Ku-band measured data, suggest that rain rate with delay could be a useful tool in examining time diversity strategies to reduce rain fade at the desired frequencies. This method has the potential to improve the dependability of satellite communication systems to cope with the difficulties associated with rain attenuation. Authors in [31] studied the deployment of 5G networks that use frequencies higher than 20 GHz and discovered the difficulties encountered by cutting-edge communication systems. By translating 1 hr rain data into 1 min intervals and using data from 77 rain-gauge network sites, their analysis suggested an ideal rain fade margin for the Peninsular Malaysian 5G network. Deploying the synthetic storm technique and ITU-R P.530-17, long-term rain attenuation data were acquired. According to the analysis, the ideal rain fade margin for a 26 GHz link in a 5G network should be between 6.50 and 10 dB for a 99.99% availability link, and between 7 and 11 dB for a 28 GHz link. Authors in [32] validated CMORPH-CRT, NOAA's bias-corrected climate prediction center morphing technique product, against rain gauge data in Peninsular Malaysia's diverse regions. The study indicated that CMORPH-CRT correlated well with rain gauge data, performing best in coastal areas, nonetheless, underestimating in foothills and overestimating in interior valleys using an 8 km × 8 km grid resolution from January 1998 to December 2018. The model performed exceptionally well in areas with moderate rainfall and correctly represented extreme events, such as the development and disintegration of a low-pressure system in Penang on November 4, 2017, which was supported by the standardized rainfall index (SPI) based on rain gauges, indicating drought conditions across Peninsular Malaysia. Authors in [33] focused on using a Hydro-Estimator to measure the rain rate across Malaysia. In their research, a sampling period of 1 hr for global coverage was measured and converted to an 1 min integration period to predict rain rate, and in turn, rain fade, using the regression technique supplied by ITU. For Peninsular Malaysia and Sabah and Sarawak regions, a slight increase in the rain rate distribution of 0.01% yearly probability was found employing the linear regression method, suggesting a possible impact of climate change on Malaysia's rain rate distribution.

In this work, the Hydro-Estimator is utilized to estimate the distribution of rain rates on a global scale, with a specific focus on Malaysia and the integration time ranged from 1 min to 1 hr to allow for detailed temporal resolution in rainfall data analysis. However, this research includes a climate change analysis component, which is different from previous studies and aligns with the growing relevance of the changing patterns of climate that may influence rainfall on global scales.

III. CRITICAL REVIEW COMPARISON OF PREVIOUS WORKS AND THE CURRENT WORK

This work applies the Hydro-Estimator method because it offers an advantage in covering regions globally. The information from the Hydro-Estimator could be used to analyze the climate change impact on the distribution of rainfall. It is projected that the rain fade will vary due to climate change. According to [34-37], there has been solid evidence pointing to increasing trends in the incidence of rain rates at intensities associated with an outage on terrestrial links over the past 30 years. However, there has been no indication from microwave links that outage rates or the incidence of fade are similarly increasing. Table II compares numerous studies that aimed to estimate rainfall rate distributions and predict climate change patterns. The current study referred to similar methodologies to the ones presented by [30-32], such as Weather Satellite Rain Gauge and CMORPH-CRT. Nevertheless, this work focused on the integration of climate change analysis into the assessment framework, which represents a pivotal advancement in understanding the dynamic interaction between rainfall patterns and environmental shifts. The present study has also extended the Hydro-Estimator method to include the spatial shapes of rain events. Having been inspired from previous works, like [30-33], which highlighted varying spatial coverages and integration times, this study represents a concerted effort to refine existing methodologies and provide innovations in the pursuit of more comprehensive and robust analyses.

IV. RAIN MEASUREMENT METHOD

Figure 1 depicts the initial step of rain measurement by inputting the data acquisition. Meteorological data collection involves the process of obtaining information from rain measurement tools including satellite images, ground-based weather stations, and weather radar systems. Other meteorological characteristics, such as wind speed, temperature, and humidity also provide important parameters for understanding atmospheric conditions [38]. Radar data are supported by satellite images, providing an additional viewpoint on weather systems and the visibility of clouds [39].

Fig. 1. Proposed block diagram of rain measurement.

Data processing, which includes procedures like integrating radar reflectivity data, validating measurements, and tackling signal distortion, is vital to improve the collected data in terms of accuracy in rainfall prediction. Accuracy is increased by adjusting to humidity and temperature impacts. Rainfall rates in various spatial and temporal resolutions can be predicted using the Hydro-Estimator method. This involves analyzing meteorological and radar data to generate rainfall intensity estimates for specific time intervals and geographical areas. In this paper, raw data from NOAA Hydro-Estimator from 2011 to 2022 are analyzed annually and for a period of 12 years on average to examine the impact of climate change on rain rate distributions in Malaysia. The data results are compared to the ITU-R 530 rain rate distribution model for verification. For the climate change research, the aforementioned Hydro-Estimator data are exhibited, with an annual exceedance chance of 0.01%, and a regression model is implemented to track the trend. According to the ITU-R 837 standard, a dependable communication system needs to achieve 99.9% signal availability time during the year [32-34]. The rain rate distribution data for 12 years are examined and compared with the ITU-R 837 model to verify that they are plausible below a margin of 0.01% error. The ITU-R 837 model is then analyzed, and the average rain rate distribution data are compared with the Hydro-Estimator rain rate data.

V. COMPUTER PROGRAM: VALIDATION AND VERIFICATION

MATLAB was used for the extraction, computation, analysis, and plotting of rain rate data from the Hydro-Estimator. The ITU-R 837 rain rate distribution model, which is regarded to be dependable or acceptable by the majority of radio engineers worldwide, was compared to 12 years' worth of rainfall data from the Hydro-Estimator, ranging from 2011 to 2022. Regarding the NOAA raw data, only the Peninsular and Sabah and Sarawak regions were chosen. In order to analyze the impacts of climate change on the distribution of rain rates, the rain rate was plotted at a yearly exceedance probability of 0.01% for 12 years. The global community decided on the 0.01% exceedance probability as a telecommunication standard for measuring signal quality, which is equivalent to about 20 min annually [33].

Figure 2 depicts the rain rate distribution for the year 2018 with 1 hr and 1 min time integration. Rainfall rate data in the regions were calculated over 1 hr, and were notably lower compared to those of the ITU-R model. A thorough examination of the rainfall rate distribution data, illustrated in Figure 3, discloses a significant difference between the Hydro-Estimator and ITU-R models, especially beyond the 0.01% probability of exceedance. However, the primary focus of this investigation is to achieve reliable results below this threshold, as this is a standard practice in the telecommunications industry, which ensures 99.99% signal availability throughout the year [32-34]. Figure 3 depicts the 12 year rain rate data for the Peninsular, Sabah and Sarawak regions. Rainfall rates in the Peninsular region vary significantly; the lowest rainfall occured in 2015, with a rain rate of 44.1128 dB, and the highest rainfall rain rate was 84.4211 dB in 2022. For the Sabah and Sarawak regions, the ranges of the rain rate are between 39.7672 dB and 101.611 dB in the years 2020 and 2013, respectively. Furthermore, the average rain rate for 12 years from 2011 to 2022 is 68.7934 dB and 78.7965 dB for the Peninsular, Sabah and Sarawak regions, respectively. Based on the data presented in Figure 3, this corresponds to a variation of 10.0033 dB or 12.69% in the exceedance percentage between these regions, suggesting significant variations in rainfall intensity.

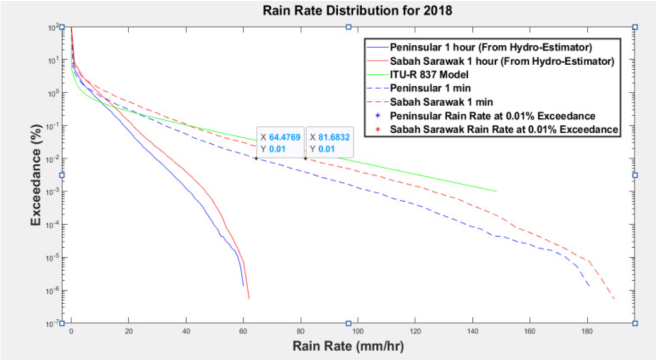

Fig. 2. Twelve year rain rate data for Peninsular, Sabah and Sarawak regions.

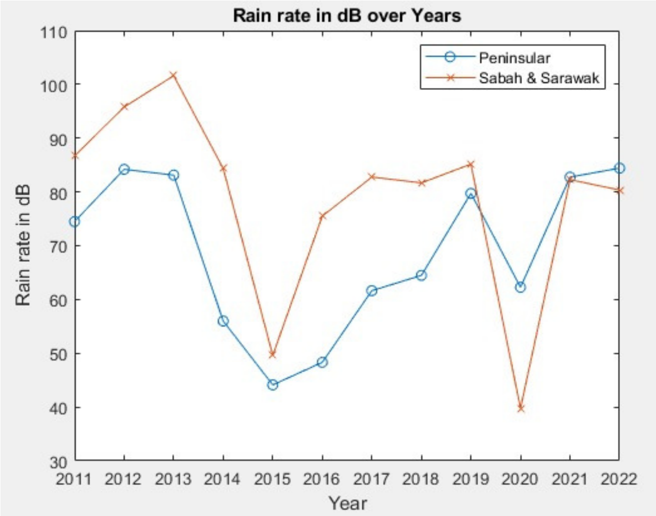

Fig. 3. Twelve year rain data for Peninsular, Sabah and Sarawak regions.

Figure 4 manifests the 12 year rain fade data for Peninsular, Sabah and Sarawak regions. Analysis of the trends reveals fluctuations in rain fade patterns across the years and regions. In the Peninsular region, rain fade varied from 10.8316 dB in 2016 to 18.3274 dB in 2022, while in Sabah and Sarawak, the rain fade ranged from 9.0147 dB in 2020 to 21.8259 dB in 2013. Calculating the average rain fade over the 12 years reveals an average of 15.35 dB for the Peninsular and 17.17 dB for Sabah and Sarawak regions. This is translated to a difference of 1.82 dB between both regions, representing a difference of 10.59% , relevant to their average rain fade.

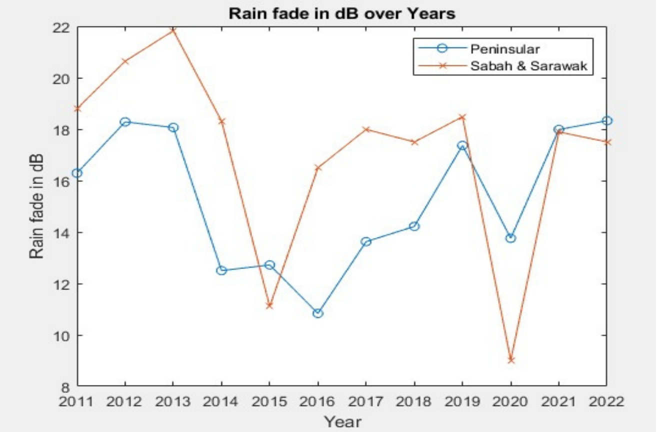

Fig. 4. Twelve years of rain fade data for Peninsular, Sabah and Sarawak regions.

Figure 5 shows the rain rate and rain fade data for the Peninsular, Sabah and Sarawak regions. The plotted graphs provide a clear visual representation of the trends in rain rate and rain fade variations, providing information about the meteorological dynamics of these areas. Some patterns illustrate the complexity of the rain rate and rain fade in Malaysia.

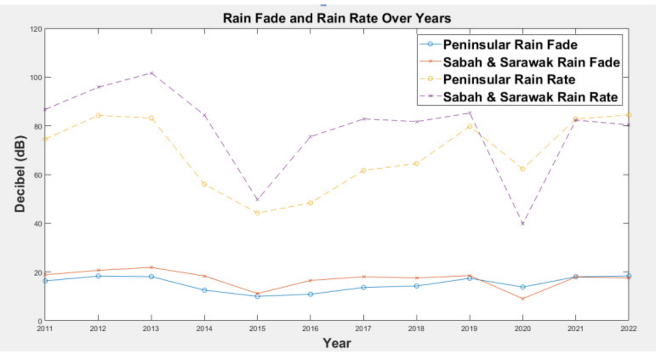

Fig. 5. Comparison of 12 year rain rate and rain fade data for Peninsular, Sabah and Sarawak regions.

VI. CONCLUSION

The current work presents the impact of climate change on rainfall distribution in Malaysia, focusing on the Peninsular and Sabah and Sarawak regions, utilizing data from the NOAA Hydro-Estimator spanning from 2011 to 2022. Rainfall events become increasingly intense as a result of human-induced greenhouse gas emissions, worsening climate change. The analysis reveals a huge discrepancy in the rainfall rate between the discussed regions, with an average gap of 12.69%, and signal loss with an average difference of 10.59%. The findings highlighted the significance of advanced methods for precise rainfall estimation and prediction, such as the Hydro-Estimator and ITU-R models, which are crucial for sustaining reliable communication infrastructure. Studies on rainfall that include climate change research yield important insights for developing mitigation plans that reduce the effects of climate change on communication networks. Addressing these challenges is crucial for ensuring the reliability of 5G networks in the face of increasingly extreme weather conditions.

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