Evaluation of Climate Change Effects on Rain Rate Distribution in Malaysia using Hydro-Estimator for 5G and Microwave Links

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ABSTRACT

Wireless transmissions at more than 10GHz can experience signal fading caused by the presence of hydrometeor particles in the atmosphere. Among these hydrometeors, rain is the largest contributor to the fading mechanism. Rain fade can be predicted or calculated using rain rate measurements. With climate change affecting the world due to the rise of carbon dioxide in the air, it is expected to affect the distribution of rainfall, which ultimately affects rain fade. This paper investigates the effects of climate change on rain rate distribution in Malaysia. Ten years of Hydro-Estimator data containing rainfall rates in Peninsular Malaysia and the Sabah and Sarawak region from 2011 to 2020 were collected and analyzed. Using the linear regression method, a small increment of rain rate distribution at 0.01% annual probability was detected for all regions, indicating a climate change effect on the rain rate distribution. For Peninsular Malaysia, the rate was 0.2356mm/hr per year while for the Sabah and Sarawak region, it was 0.4046mm/hr per year. An increase in the rain rate would increase the rain fade, causing signal losses and

distortions in high-frequency wireless communication signals. The evaluation of climate change effects on the rain rate and rain fade distributions can help in developing a long-term prediction of the signal performance in 5G systems and high-frequency radio link frequencies due to hydrometeors.

Keywords-hydrometeor; ITU-R model; millimeter-wave band; rain fade; 5G concerns; wireless transmission

I. INTRODUCTION

The use of wireless communication technology has become essential in daily life. With the technology getting more advanced, more data are transmitted and received in various forms of complex multimedia, including images, videos, and advanced mobile applications that demand more bandwidth and faster data transmission [1-4]. Thus, mobile communication is in dire need of improvements to meet the growing demands. The development of the 5G radio communication system includes wireless backhaul services that use higher frequencies, such as millimeter waves (mmWave), to meet the need for more flexible wireless data services [5-7]. Ideally, the mmWave band, which is a frequency range from 30 to 300 GHz, is considered the most optimal region to achieve high channel bandwidth, while at the same time degrading the interference, allowing high-speed data communication, and improving propagation characteristics, making it more homogeneous [8].

However, the implementation of 5G faces great challenges, as higher frequency signals experience significant signal losses due to scattering and absorption by hydrometeor particles such as rain, clouds, fog, and sleet in the atmosphere. The largest and most dynamic contributor to these losses is rain fade, as it can cause interruption or complete loss of signal when the rain becomes too intense [9-10]. Rain events are highly dynamic in terms of space and time since they can shift to different places at high speed and last from a few minutes to hours. Typical heavy rain events can move up to 8 m/s and can be extremely challenging to measure [11]. In satellite communications, such as the Ka-Band satellite channel, system performance is severely degraded due to atmospheric fading effects, especially rain attenuation [9-14]. Moreover, in tropical regions that suffer severe weather conditions, heavy rainfall, and higher rain intensity, the effect on radio links becomes significantly high for frequencies above 7 GHz [13-15]. This poses greater challenges to optimizing the 5G functionality in a tropical country like Malaysia. Furthermore, with global climate change, the rain trend is expected to change over the years [16], considerably affecting the rain fade of 5G links.

Rain attenuation or rain fade can be estimated from the rainfall rate in mm/hr. Rain gauges, radars, and weather satellites provide rainfall rate estimation in mm/hr and can be converted to rain attenuation or fade in dB using the standard ITU-R 838 model [11-12, 17]. The plot of annual rain attenuation or rain fade distributions for statistical analysis typically requires a 1-minute integration time of annual rain rate distribution, according to the ITU P.837 and 530 recommendations. Unfortunately, the methodological approach to predict rain attenuation in any terrestrial radio link does not perform well in tropical climates because it is based on data collected from temperate regions [18]. Moreover, the existing theoretical ITU rain model lacks climate change features [15]. Climate change affects rain intensity and frequency. This evidence was further verified in [19], which stated that climate change causes an increase in the frequency and intensity of extreme rainfall. In [20], human-caused climate change was found to intensify the heaviest downpours and increase flooding events, as the increase in water vapors due to global warming creates more moisture. Extreme weather events have become more frequent and intense due to climate change, for example, tropical cyclone activity with increased intensity, more hot days and hot nights, heat waves, and more heavy precipitation [21]. Therefore, it is important to consider the effect of climate change on the rain distribution to effectively analyze rain fade. This study considered 10 years, from 2011 to 2020, of Hydro-Estimator data by the National Oceanic and Atmospheric Administration/National Environmental Satellite Data and Information Service (NOAA/NESDIS) [22] to investigate the effect of climate change on rain rate distribution in Peninsular Malaysia and Sabah and Sarawak regions. Table I compares different meteorological measurement methods.

TABLE I. COMPARISON OF METEOROLOGICAL MEASUREMENT METHODS

Parameter	**Meteorological measurement methods**			
	Rain gauge	**Rain radar**	**Weather satellites**	**Hydro-Estimator**
Spatial coverage	Hundreds of m to a few km	Hundreds of km	Continents or globally	Globally
Temporal sampling time	1 min to 1 h	5 to 15 min	30 min to 1 h	1 h

Meteorological measurements are typically used for hydrological purposes, such as flood risk prediction and agriculture planning. Most of these measurement sources are adequate for such endeavors but, according to ITU, for rain fade prediction on microwave or millimeter wave radio links, accurate rain rate measurements preferably with 1 min sampling or integration time are needed. Most of these measurements provide rainfall data in mm/hr with different integration or sampling times. However, these can be converted to 1 min integration or sampling time using a regression equation provided by ITU to convert various integration times to 1 min integration time to predict rain rate and consequently, rain fade [17]. Rain gauges provide the most accurate rain rate measurement and are often used by other measurement sources as "ground truth" for validation and calibration purposes. In addition, the cost per rain gauge is significantly cheaper compared to other sources. However, the maximum spatial coverage for a rain gauge is typically around hundreds of meters, and the cover of an entire country would require an extremely large amount of rain gauges.

Weather radars or rain radars lie between rain gauges and weather satellites. Rain radars provide significantly better spatial coverage compared to rain gauges. Typically, only several rain radars are needed to cover a small country. Rain radars rely on measuring reflected electromagnetic waves from rain events at the *S* or *C* band to measure rain rate. The sampling times for rain radars are longer than rain gauges, ranging from 5 to 15 min between scans, which slightly reduces their accuracy [9]. Weather satellites provide the best spatial coverage since they can measure rain rates globally, but with a longer sampling time of 30 min to 1 h and with a maximum of 37 mm/hr rain rate measurement in the case of EUMETSAT weather satellites. Additionally, weather satellites are less accurate as they observe rain events from above and calculate rain rates by measuring the temperature of the cloud tops using infrared devices [22].

The Hydro-Estimator provides a global map of rain rate using global measurement sources, including rain gauges, rain radars, and weather satellites, blending them with numerical weather prediction models using specific techniques to increase accuracy [22-23]. The sampling time of the Hydro-Estimator is 1 h for global coverage, but this can be solved by using a regression technique provided by ITU to convert 1 h to 1 min integration time for rain rates, and consequently, rain fade. This platform can be a great asset to provide rain rate measurements, especially in areas without rain gauges and rain radars [24]. Furthermore, this platform is freely available, quick, and easy to access compared to other sources. This study used Hydro-Estimator data to obtain rain rate measurements and investigate the effect of climate change on rain fade of 5G millimeter wave backhaul links or other wireless communications that use frequencies above 10 GHz.

II. THEORETICAL HYDRO-ESTIMATOR ALGORITHM

The Hydro-Estimator is a meteorological platform that contains rainfall rate information and is currently operated by NOAA/NESDIS in the United States. It combines and consolidates rain rate data from rain gauges, rain radars, and weather satellites to provide rain rate data on a global scale. The data have 1 h sampling time but can be converted to 1 min integration using the regression model in ITU-R 839:

$$R_1(p) = a[R_\tau(p)]^b \qquad (1)$$

where $R_\tau(p)$ is the rain rate with 1 h sampling rate at probability $p\%$ and $R_1(p)$ is the new 1 min sampling time rate at the same probability. Coefficients a and b carry fixed values of 0.564 and 1.288, respectively. It is worth noting that the raw data in the Hydro-Estimator need a direct conversion to be interpreted as rain rate in mm/hr. The rain rate can be calculated from the raw data using the following equation provided by NOAA [22].

$$R = (value - 2) * 0.3048 \qquad (2)$$

where R is the rain rate in mm/hr and *value* is the raw data.

III. COMPUTER PROGRAM: VALIDATION AND VERIFICATION

The process of extracting, calculating, analyzing, and plotting rain rate data from the Hydro-Estimator was performed in MATLAB. Hydro-Estimator rain rate data between 2011 and 2020 were compared to the ITU-R 837 rain rate distribution model, which is regarded as reliable or acceptable by most radio engineers. The yearly rainfall rate distributions between 2011 and 2020 were compared between Hydro-Estimator and ITU-R 837 along with the 10-year average rain rate distribution for verification purposes. The annual rain rate distribution was calculated using the probability exceedance method, which is the percentage probability of how much rain rate is equal to or exceeded at that probability level. The calculation method for exceedance probability is:

$$P(\%) = \frac{CF(max) - CF}{CF(max)}(100\%) \qquad (3)$$

where $P(\%)$ is the exceedance probability, $CF(max)$ is the maximum cumulative frequency of the rain rate and CF is the range of all cumulative frequencies of the yearly rain rate. The next step was to plot the rain rate with a 0.01% exceedance probability yearly from 2011 to 2020 to observe the effects of climate change on the rain rate distribution. The exceedance probability of 0.01% was selected as it is a telecommunication standard by the global community to measure signal quality. A yearly 0.01% exceedance probability represents approximately 20 min of total time in a year.

IV. PERFORMANCE EVALUATION

Table II shows a comparison of similar studies in estimating rain rate distribution using the methods in Table I.

TABLE II. COMPARISON OF RELATED WORKS

Study	Methods	Spatial area coverage	Integration time	Spatial shapes of rain events	Climate change analysis	Maximum range of rain rate
[1]	Hydro-estimator	Globally	1 h	Yes	No	~100 mm/hr
[25]	Rain gauge	~2.8 km^2	1 min	No	No	~250 mm/hr
[26]	Rain radar and rain gauge	~ 3 to ~28 km^2	5-6 min	Yes (rain radar)	No	~250 mm/hr
[27]	Weather satellites, rain radar, and rain gauge	~3 km^2 (rain gauge), ~100 km^2 (rain radar)	1 h (for all)	Yes (rain radar and weather satellite)	No	~120 mm/hr
This study	Hydro-Estimator	Globally	1 h	Yes	Yes	~100 mm/hr

This study used Hydro-Estimator data to integrate a climate change analysis on rain rate distribution. In [15], it was stated that over the past 30 years, there is growing proof suggesting that the incidence of rain rates at intensities associated with an outage on terrestrial links has exhibited increasing trends, but there is no evidence of increased outage rates or fades of microwave links. This study provided evidence that trends in the size of rain events lead to changes in the relationship between point rain rates and rain fade. However, these trends have been shown to vary significantly across the UK. Malaysia, however, has a different climate from the UK. Therefore, this can result in different conclusions on how climate change has affected the rain rate and rain fade.

A. Simulation Environment

All extraction, conversion, and plotting processes were performed in MATLAB. Rain rate data in 2011-2020 of Peninsular Malaysia and the Sabah and Sarawak region were downloaded from the Hydro-Estimator in raw format, then were extracted, and converted to mm/hr using (2). Subsequently, the data were analyzed for their exceedance probability distribution using (3). The obtained results were analyzed yearly and 10-year averaged and compared to the ITU-R 837 rain rate distribution model for verification. Each year was plotted with a 0.01% exceedance probability, and a regression model was used to observe the trend.

B. Simulation Parameters

Figure 1 shows the results for 2011 with 1 h and 1 min integration. This step was performed for each year from 2011 to 2020. The rain rate distributions of Peninsular Malaysia and the Sabah and Sarawak region with 1 h integration time were significantly lower when compared to the ITU model. However, rain rate distribution results from the same regions and with 1 min integration, after conversion using (1), appears to be plausible when compared with the ITU-R model, particularly for the Sabah and Sarawak region. This is significant since the ITU-R 837 model was developed based on numerous rain rate measurements with a 1-minute integration time. Further analysis of the rain rate distributions in Figure 1 shows a wide difference between the Hydro-Estimator and ITU-R models, beyond 0.01% exceedance probability. However, this study focused on achieving plausible results down to 0.01% exceedance probability only, since this is a common quality standard practiced by telecommunication industries, and translates to 99.99% signal availability throughout the year [28-29].

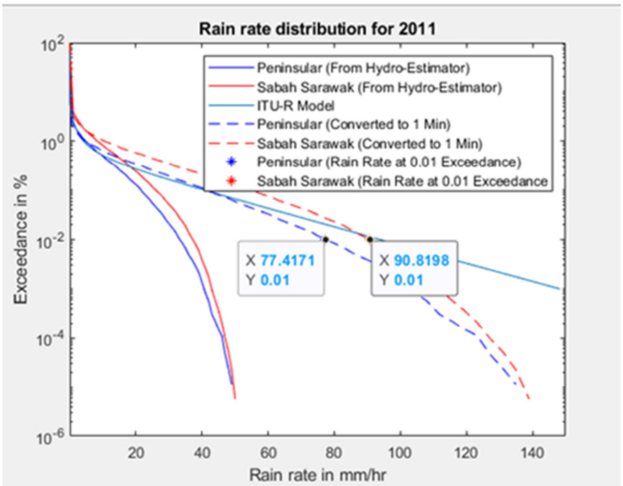

Fig. 1. Rain rate distributions for 2011 compared with the ITU-R model.

C. Ten Year Rain Rate Distribution

Figures 2 and 3 show the rain rate data at 0.01% exceedance probability for each year between 2011 and 2020 for the Peninsular Malaysia and Sabah Sarawak regions, respectively. By performing linear regression analysis, the figures show increasing trends of rain rate distribution throughout these years. For Peninsular Malaysia, the rate was 0.2356 mm/hr per year while the Sabah and Sarawak region had 0.4046 mm/hr per year. This shows that climate change affects the distribution of rain rates in tropical regions such as Malaysia.

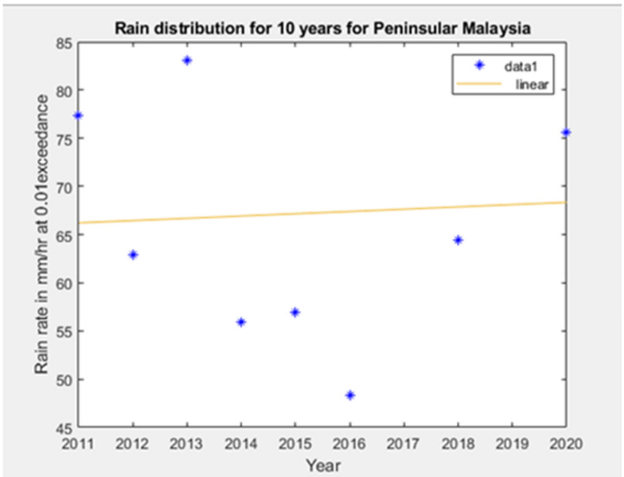

Fig. 2. Rain distribution trend from 2011-2020 for Peninsular Malaysia.

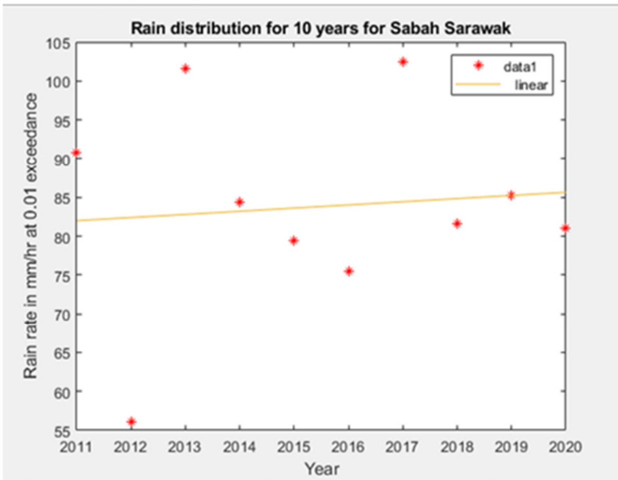

Fig. 3. Rain distribution in 2011-2020 for the Sabah and Sarawak region.

D. Average Rain Rate Distribution

The rain rate distribution was further compared with the ITU-R 837 model. Figures 4 and 5 show the results for each year for Peninsular Malaysia and the Sabah Sarawak region, respectively. Figure 6 shows the 10-year average of the rain rate distribution result and its comparison with the ITU-R 837 model. Figure 6 shows that the Hydro-Estimator rain rate distribution had a slight agreement with the ITU-R 837 model for both the Peninsular Malaysia and the Sabah and Sarawak region. The Peninsular Malaysia result seems to underestimate the ITU-R model, especially at a lower exceedance probability, while the two models seem to be in more agreement for the Sabah and Sarawak region. The differences between the Hydro-Estimator and the ITU-R results can be attributed to variations in rain rate distribution from year to year, as shown in Figures 4 and 5. It can be deduced that Hydro-Estimator provides reliable rain rate distributions and can be further used for rain fade simulation on microwave and millimeter wave links.

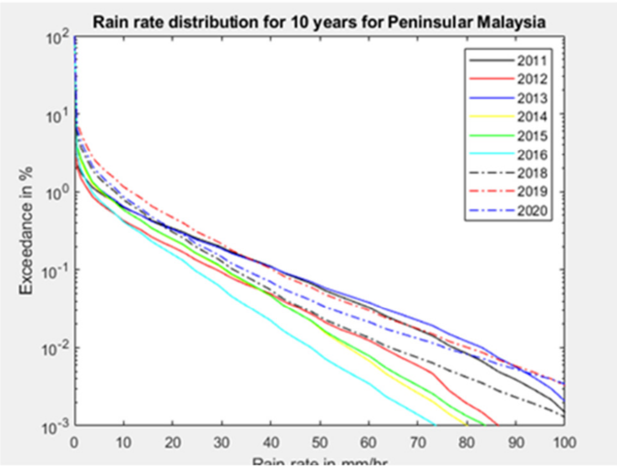

Fig. 4. Rain rate distribution from 2011 to 2020 for Peninsular Malaysia.

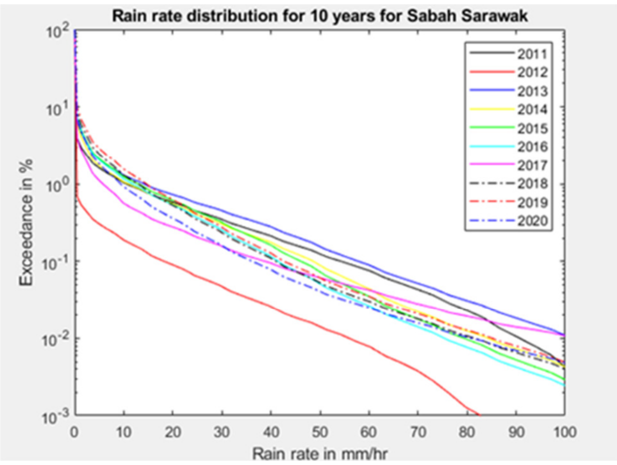

Fig. 5. Rain rate distribution from 2011 to 2020 for the Sabah and Sarawak region.

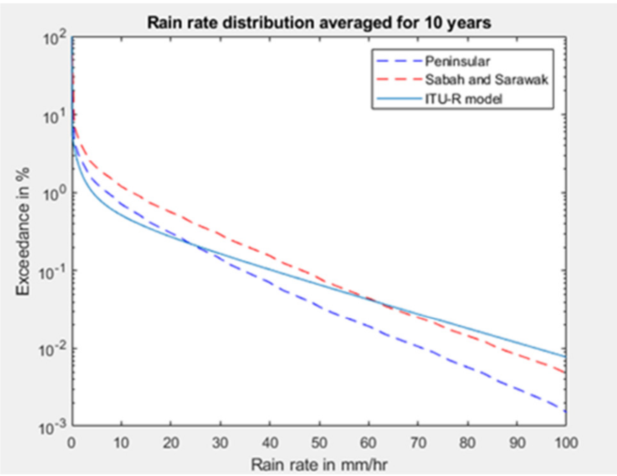

Fig. 6. Comparison of the average ten-year rain rates of the proposed with the ITU-R model.

V. CONCLUSIONS

This study used Hydro-Estimator data from 2011 to 2020 to plot the trend of rain rate distribution over Malaysia. The simulated rain rates from the Hydro-Estimator were compared with the ITU-R 837 model for verification. The results showed a reasonable agreement between the data and the model. The results showed an increasing trend in rain rate distribution for the Peninsular and Sabah and Sarawak regions in Malaysia, and indicate that climate change had an impact on rain rate distribution over the years. The change in rain rate distribution over the years affects rain fade distribution and consequently, overall signal performance for high-frequency links, including wireless backhaul 5G, Ka/Ku Band communication satellites, and terrestrial microwave links.

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