Investigation of time diversity gain for earth to satellite link using rain rate gain

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ABSTRACT

The utilization of satellites for communication systems has expanded considerably in recent years. C and Ku-bands of frequencies are already congested because of high demand. Future directions of satellite communications are moving towards Ka and V-bands. Earth to satellite communications are moving towards higher frequency bands in future which are more sensitive to environment. Rain causes severe degradation in performances at higher frequency bands specially in tropical regions. Several mitigation techniques are proposed to design reliable system. Time diversity is one of the potential candidate for it. However, time diversity analysis requires measured rain attenuation data. For future high frequency link design those data are not available at most of the places. This thesis proposes a method to utilize 1-minute rain rate to analyze time diversity technique at any desired frequency. This paper proposes a method to utilize 1-minute rain rate to analyse time diversity rain rate gain. In proposed method, it is assumed that rain rate gain with delay can represent rain attenuation gain with delay for same period of time at same location. The characteristics of rain rate and rain attenuation almost same because the attenuation causes due to rain. One year measured rain rate in Malaysia is used to predict rain rate gain. The measured gain at 12.225 GHz signal is compared with that predicted by ITU-R based on rain rate measurement and is found good agreement. Hence it is recommended that the time diversity gain can be predicted using measured rain rate for any desired frequencies.

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1. INTRODUCTION

Earth-to-satellite links that operate at frequencies higher than 10 GHz (Ku, Ka, and V bands) are strongly affected by propagation impairments especially by precipitation the tropical climate and equatorial climate experience heavy precipitation all over the year [1]. Therefore, the satellite communication system performance suffers from severe degradation at high frequencies [2]. It is not practical to include very high fixed fade margins in link budgets as a compensation for the great propagation impairments due to effects of transmitter power limitations. In order to overcome such problems, implementation of Fade Mitigation Techniques (FMTs) becomes significant to ensure the continuity of system availability [3].

FMTs have to take in consideration the system performance aims, the system architecture parameters and the frequency bands in operation. Time diversity is one of the best choice among FMTs in an

Earth-satellite links to encounter severe channel fading in terms of cost and benefits [4]. The performance of time diversity is generally evaluated using measured rain attenuation time series with and without delay of time. It calculates the joint exceedance of rain attenuation probability both with and without delay [5]. Time diversity gain is the indicator for improvement. An empirical model to predict time diversity gain function was derived in Malaysia based on measured data to estimate rain attenuation exceedance probability [6]. Similar gain model as a function of delay time, attenuation level and frequency in operation was proposed in [7, 8], two methods were developed for calculating joint exceedance rain attenuation probability which represent the complementary cumulative distribution function of rain attenuation that follows the lognormal distribution.

In rain attenuation analysis along earth-to-satellite links, it can be observed obviously that attenuation of signal is directly related with intensity of rain occurred [9]. Hence the variations of attenuations must follow the variations of rain intensity along the propagation path [10-12]. onsidering this fact in mind, real time rain intensity variations can be utilized to evaluate time diversity improvement on earth-to-satellite links which is conventionally estimated using real-time rain attenuation data [13]. This paper investigates the possibility to use rain rate time series to estimate time diversity gains for earth-to-satellite links [14-17]. Measured rain rate and rain attenuation data at Ku-band are used for investigation.

The equation of the marginal distribution which is converted conventional cumulative probability distribution function (CDF) is shown in below [7]

$$P(A) = P[A(t) > A] = \int_A^\infty \xi[A(t)]dA \tag{1}$$

where $\xi(A)$ is the density function of rain attenuation A(t), and P(A) is its integral, calculated for all time t of the rain attenuation time series. The joint distribution is given by [7]

$$P[A(t) > A, A(t+T) > A] = \int_A^\infty \int_A^\infty \gamma[A(t), A(t+T)]dA(t)dA(t+T) \tag{2}$$

where $\gamma[A(t), A(t+T)]$ is the joint probability density function of A(t) and A (t +T) with delay time T. Most of Time Diversity studies follow 1 to 60 minutes delay of times as shown in Figure 1(a) and 1(b).

The complementary cumulative distribution function of rain attenuation conditioned to the time delay can be used to estimate the performance of time diversity as follows: A(t) refers to rain attenuation without time delay, while T is defined as a time diversity delay and A (t +T) refers to rain attenuation shifted of T.

This represents the time of percentage exceeded for minimal rain attenuation and the signal of satellite to earth will be subjected to minimal rain attenuation as a result of using time diversity technique and is expressed by the model

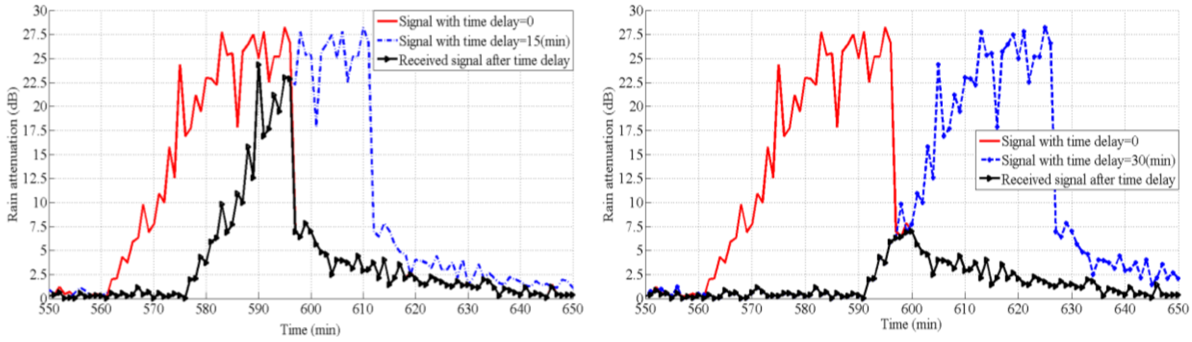
$$A_{TD} = \min\,[A(t), A(t+T)] \tag{3}$$

There is a need to make a comparison of the original time series of attenuation and the same time series delay by given time interval in order to get the lowest attenuation value as explained in (3). An illustrative example for the use of time delay technique is presented in Figure 1. An event of measured signal on the satellite-Earth link is applied. It is clear that the maximum attenuation of the signal without time delay is about 28 dB, but after applying time diversity technique with time delay of 15 and 30 minutes, the maximum rain attenuation is 24 and 7 dB respectively.

The signal delays T-minute or in the range 1-60 minutes instantaneously. From delaying the signal may be written as the probability from the diversity combination experiences an attenuation greater than A [11].

$$prob(A_{div} \geq A) = 1 - P[(A_p\ or\ A_T) < A] \tag{4}$$

The time-diversity gain (in dB) for a specified exceedance probability (p) as A_pl (non-diversity). The cumulative distributions of rain attenuation A, with different time delays were analysed based on measurements done in Malaysia [12] are shown in Figure 2. From figure, it is clear that more than 20 dB improvement is possible through time diversity technique.



(a) (b)

Figure 1. An Example, which illustrates the use of time diversity technique and its improvement in the signal of a satellite-Earth link for an event, measured at Penang-Malaysia on October 21, 2009, (a) Delay time T=15 minutes, (b) Delay time T=30 minutes [6]

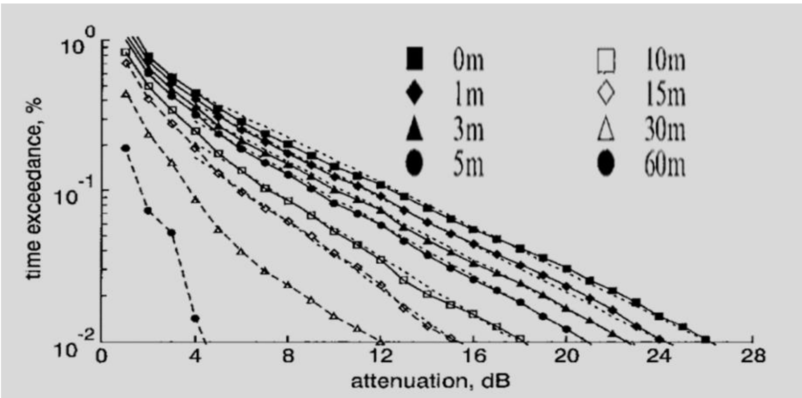


Figure 2. Cumulative distributions of rain attenuation with time diversity for delays in the range of 1-60 minutes measured at 12 GHz in Malaysia [12]

Time diversity gain is the value of the difference in dB between rain attenuation of the communication signal and the same signal with defined time delay [18]. Therefore, the time diversity gain is used to evaluate the time diversity improvement in performance as a fade mitigation technique for rain attenuation [14]. Time diversity gain can be expressed instantaneously by the following equation.

$$GA_{TD} = A(t) - A_{TD} \text{ (dB)} \tag{5}$$

where GA_{TD} is time diversity gain using rain attenuation.

The difference at equal probability, time diversity statistical gain can be described by the rain attenuation $A_{(\%P)}$ exceeded from the marginal distribution [19] as the long-term annual probability distribution and $A(T)_{(\%P)}$ of the joint distribution relative to delay T:

$$GA_{TD(\%p)} = A_{\%p} - A(T)_{\%p} \tag{6}$$

However, time diversity analysis requires measured rain attenuation data. For future high frequency link design those data are not available at most of the places [20-21]. This paper proposes a model to utilize 1-minute rain rate to predict time diversity gain at any desired frequency. In proposed method, it is assumed that rain rate with delay can represent rain attenuation with delay for same period of time at same location. This assumption is valid as long as the attenuation causes due to rain. One year measured 1-minute integration rain rate at International Islamic University Malaysia is used for analysis.

2. RAIN RATE DATA COLLECTION

The rain rate data were collected for 1-year 2014, from January 1 to December 31 at International Islamic University Malaysia (IIUM) Kuala Lumpur campus (3.257° N, 101.7325 °E). A real-time rain gauge of Casella type with 0.2 mm bucket size was used to measure the data. The data collection setting was 10 second integration time. Readings were displayed by a personal computer, which was programmed to convert the data in 1- minute integration time.

3. PROPOSED TIME DIVERSITY GAIN USING RAIN RATE

Rain intensity and attenuation caused due to rain are closely related to each other. Based on the rain attenuation equation with time delay, the complementary cumulative distribution function of rain rate with time delay is proposed to be used to estimate the performance of time diversity as follows:

R(t) refers to rain rate without time delay, *R (t+T)* refers to rain rate shifted of *T*. while T is defined as a time diversity delay. (7) to (9) are proposed using rain rate time series as follows:

$$P(R) = P[R(t) > R] = \int_R^\infty \xi[R(t)]dR \quad (7)$$

where $\xi(R)$ is the density function of rain rate R(t), and P(R) is its integral, calculated for all time t of the rain rate time series. The joint distribution is proposed as

$$P[R(t) > R, R(t+T) > R] = \int_R^\infty \int_R^\infty \gamma[R(t), R(t+T)]dR(t)dR(t+T) \quad (8)$$

where $\gamma[R(t), R(t+T)]$ is the joint probability density function of R(t) and R (t+T). Hence the rain rate with time diversity can be expressed as follows

$$R_{TD} = \min\,[R(t), R(t+T)] \quad (9)$$

Conventionally used time diversity gain is the value of the difference in dB between rain attenuation of the communication signal and the same signal with defined time delay. The proposed time diversity gain using rain rate can also be defined instantaneously as the difference of rain rate with and without delay in mm/hr using (6) as follows:

$$GR_{TD}=R(t)-R_{TD}(mm/hr) \quad (10)$$

The difference at equal probability, time diversity statistical gain can be found by the rain rate $R_{m\%p}$ exceeded in the marginal distribution as the long-term annual probability distribution and $R_{\%p}$ of the joint distribution relative to delay *T*:

$$GR_{TD(\%p)} = R_{m\%p} - R_{\%p} \quad (11)$$

This Figure 3 shows the rain rate from different percentage which was derived by using the program and was transmitted twice with time delay, T. This Figure 3 shows that rain rate decreases as T increases. Thus, the time delay with several minutes especially in small cumulative time percentage is shown large diversity gain in the Figure 4. Most probably this method is powerful in future for rain fade mitigation. In future this technique will be demandable for the transmitter and receiver. This technique can be used by lower cost in the system for millimetre band satellite systems. If time diversity with time delay, T, effective rain rate can be reduced 10, 15, 30, 40, 52 and 68 mm/hr at 1, 3, 5, 10, 20 and 30 minutes delay even at cumulative time percentage at 0.01%. Variation in cumulative time percentages as a function of delay time, T.

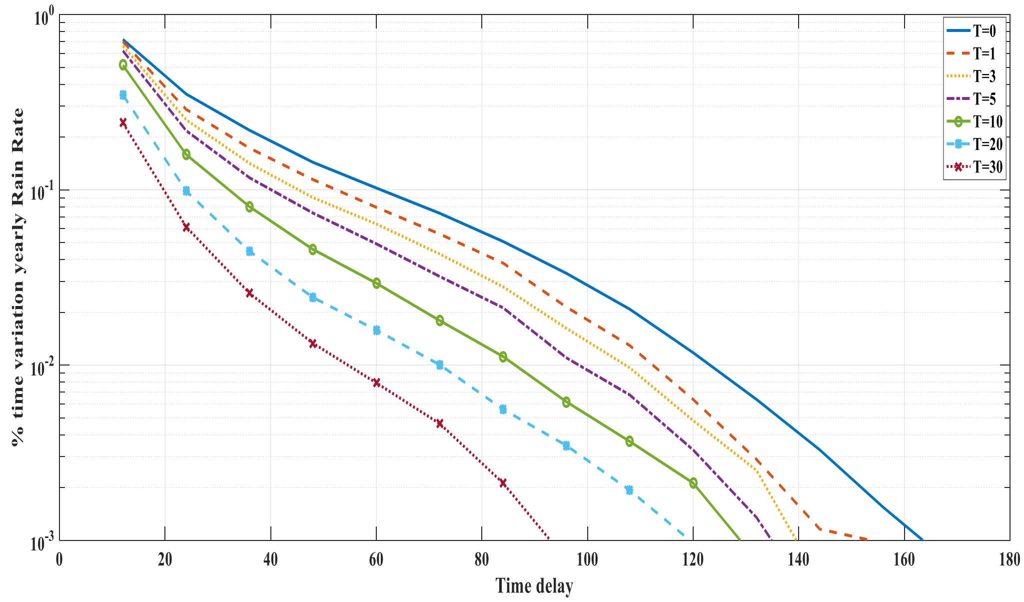


Figure 3. Proposed complementary cumulative distributions of 1-minute rain rate measured at IIUM with several time delays for the year 2014

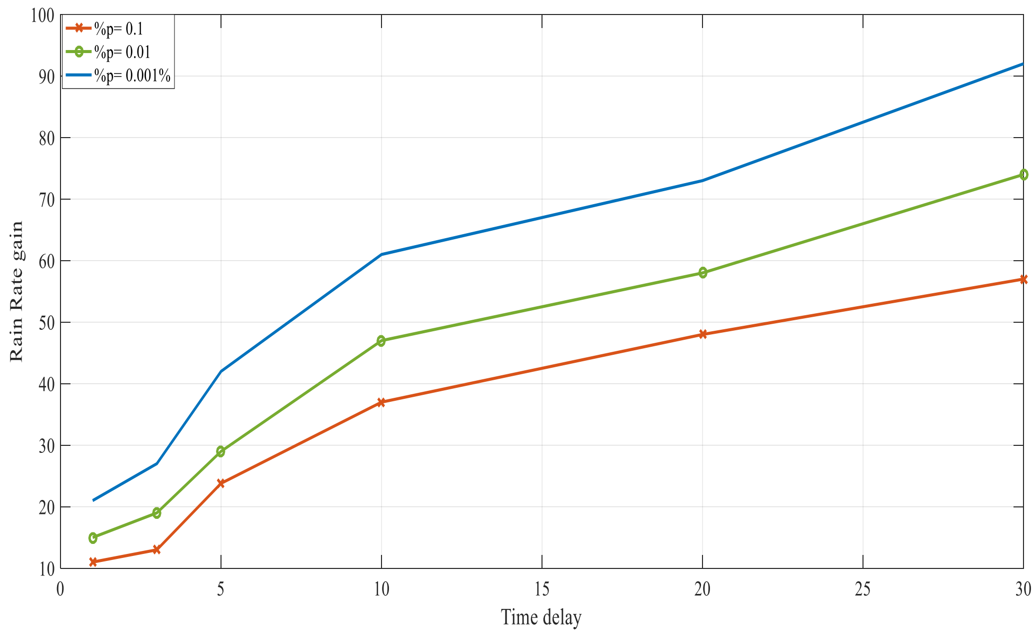


Figure 4. Variations of proposed time diversity rain rate gain in mm/hr for different percentages of time with several time delays

4. PROPOSED TIME DIVERSITY GAIN USING PREDICTED ATTENUATION

Based on measured rain rate at 0.01% without and with time delay are estimated from Figure 4 for 0, 1. 3, 5, 10, 20, 30 minutes and found 125, 115, 108, 97, 85, 73, 66 mm/hr respectively. The cumulative distributions of rain attenuation A by considering $R_{0.01\%}$ as 125, 115, 108, 97, 85, 73, 66 mm/hr rain rates are predicted by ITU-R equations (1 to 9) [17] and shown in Figure 5. In prediction, International Islamic University Malaysia Kuala Lumpur campus is considered as receiver location and MEASET-3 as satellite with 12.255 GHz frequency for transmission and an elevation angle of 77.4°. From figure, it is clear that more than 12 dB improvement are possible through time diversity technique. For illustration, at 0.01%, the rain attenuation level without applying time diversity technique is 29.4 dB. While, the rain attenuation levels are 27, 25.5, 24, 21.5, 19.6, 15.6 dB diversity with time delays of 1, 3, 5, 10, 20 and 30 min respectively. Figure 6 shows strong similarities with results.

Based on (6), the time diversity gain is estimated using Figure 6 with 0.1%, 0.01% and 0.001% and shown in Figure 7. Table 1 presents the gain with 1, 3, 5, 10, 20 and 30 minutes delays. It is obvious that gain increases with longer delays for all percentage of time. For same period of delay, gain at lower outages are always higher than that of higher percentages. These findings are found very similar with those obtained by measurements and shown in Figures 5 and 6.

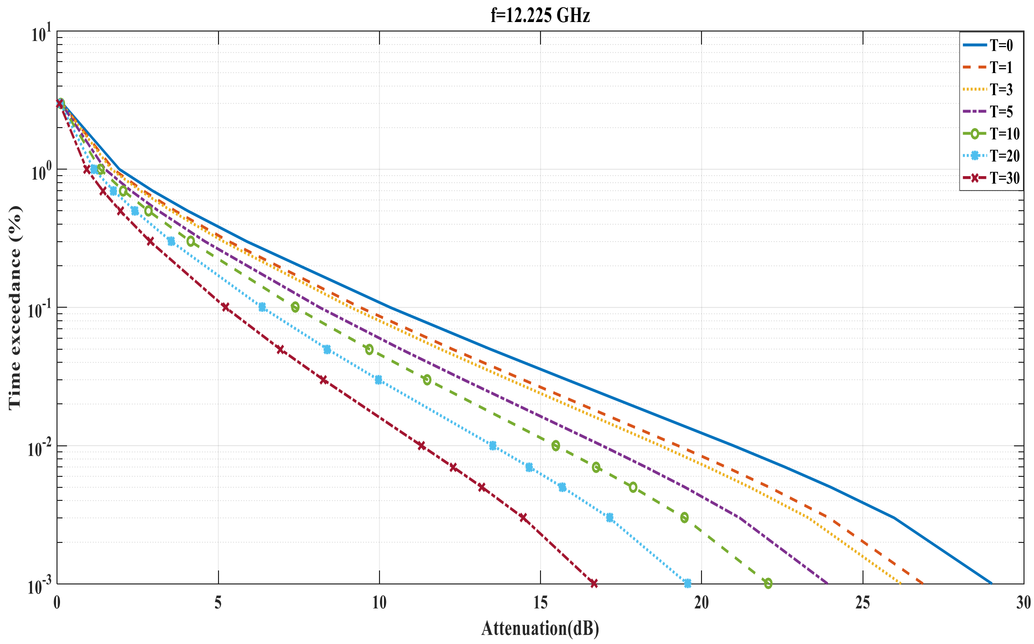


Figure 5. Complementary cumulative distributions of predicted rain attenuation for satellite-earth link at 12.225 GHz with 0, 1, 3, 5, 10, 20 and 30 minutes time delays

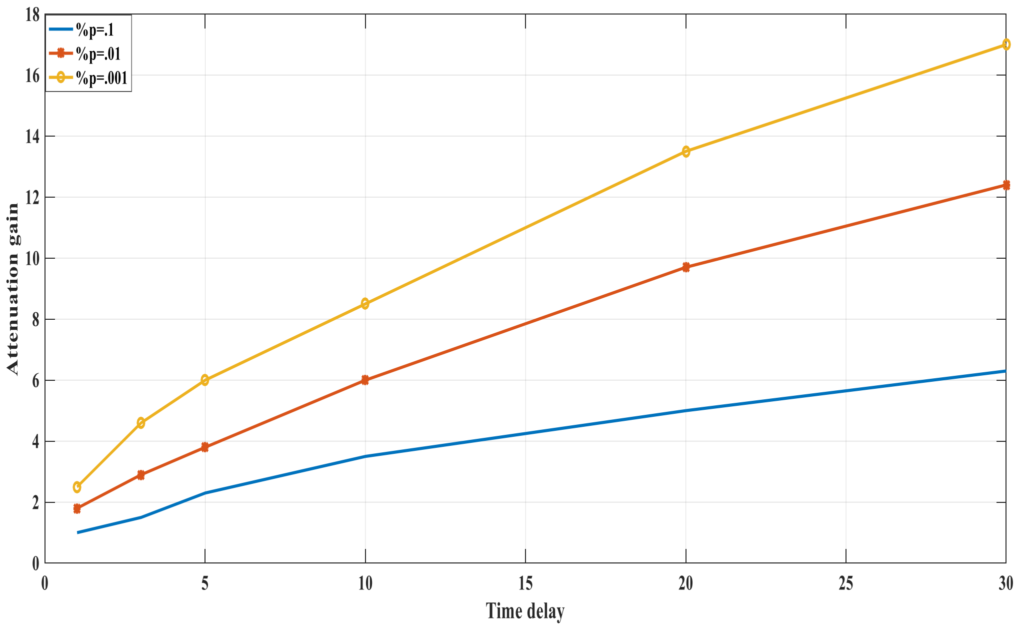


Figure 6. Predicted time diversity rain attenuation gain for different percentages of time with several time delays

The time diversity gain was estimated using measured rain attenuation distribution from the MEASET-1 satellite signal transmitted at 12 GHz at the KualaLumpur, Malysia with an elevation angle of 77.4° [18]. The measured gain at 0.01% is compared with those predicted in Table 1 with delays of time 1, 3, 5, 10, 20 and 30 minutes and presented in Figure 7. It is obvious that the gain is almost similar until 10 minutes delay and predicted gain is 1.6 dB higher for 30 minutes delay.

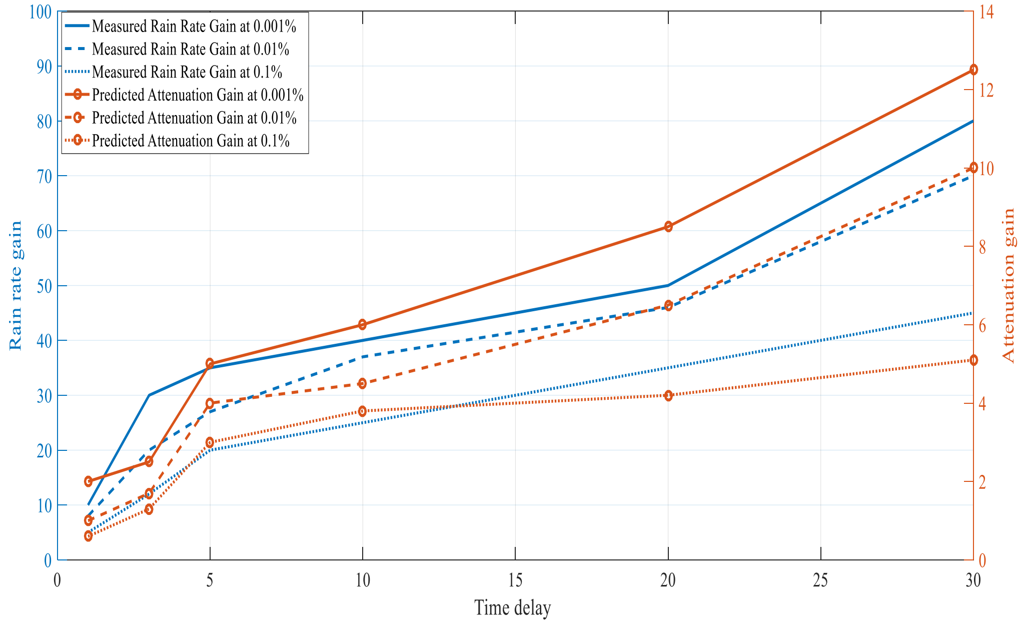


Figure 7. Comparison Measured time diversity rain rate gain and predicted rain attenuation gain for different percentages of time with several time delays

Table 1. Predicted rain attenuation gain at 12.225 GHz

	%p		
Time	0.1	0.01	0.001
1	1	1.8	2.5
3	1.5	2.9	5
5	2.3	3.8	6
10	3.5	6	8.5
20	5	9.7	13.5
30	6.3	12.4	17.5

Hence it is recommended that the time diversity gain can be predicted using measured rain rate with very good accuracies and its shown in Figure 8. Since, measured 1-minute rain rate is available in almost all locations of the world, it can be utilised to predict time diversity gain for any desirable frequencies.

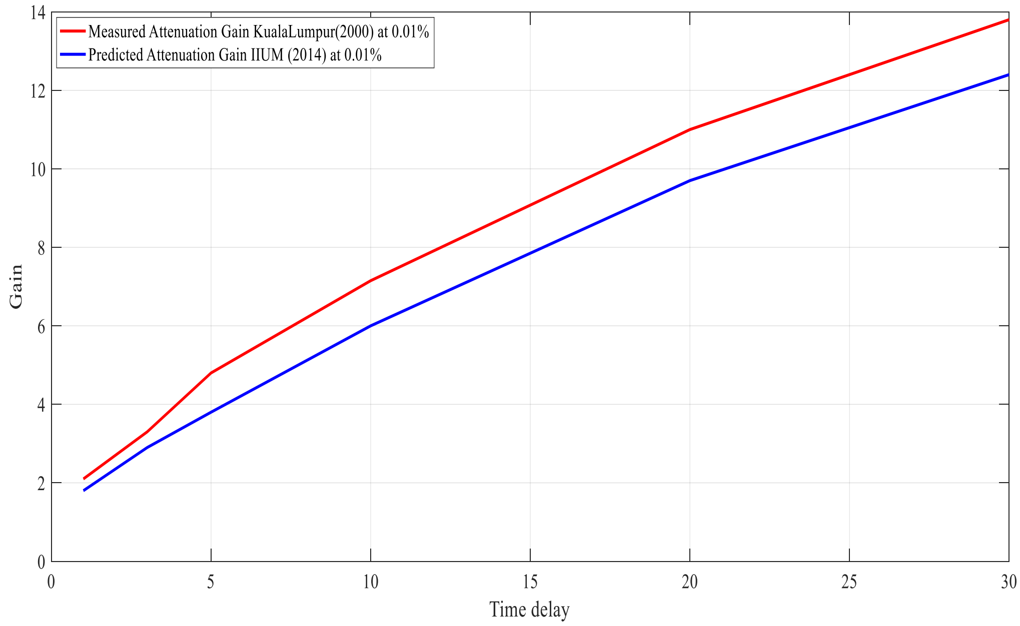


Figure 8. Comparison between the measured attenuation gain with those predicted at time delays of 1, 3, 5, 10, 20 and 30 minutes for 12 GHz

5. CONCLUSION

Time diversity is one of the techniques proposed for mitigation of rain fade. It is a clear, the technique of time diversity is suitable for applications such as data transfer process that not needed until the rain fades over. However, time diversity analysis requires measured rain attenuation data which are not available at most of the places. This paper proposes a method to utilize 1-minute rain rate to analyse rain rate gain which is used for time diversity gain at any desired frequency. It is assumed that rain rate gain with delay can represent rain attenuation gain with delay for same period of time at same location. Measured 1-year rain rate distribution with and without delay were used for rain rate gain. Measured rain rate is used to predict rain attenuation distributions by ITU-R method. This distribution with and without delay is found very similar characteristics with those obtained by measurements. Predicted rain attenuation distribution is analysed to estimate attenuation gain and is compared with measured attenuation gain for 12.225 GHz. The predicted attenuation gain is found close to measured one. Since, measured 1-minute rain rate is available in almost all locations of the world, it is recommended to be utilised to predict time diversity gain for any desirable frequencies.

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REFERENCES

[1] S. L. Jong, M. D'Amico, J. Din and H. Y. Lam, "Performance of time diversity technique in heavy rain region," *2014 International Symposium on Antennas and Propagation Conference Proceedings*, Kaohsiung, 2014, pp. 575-576.
[2] N. W. M. Saad, A. F. Ismail, K. Badron, F. Isa, J. Din and A. R. Tharek, "Proposed rain fade mitigation technique for Ka-band space-Earth links in tropical climate," *2013 IEEE 11th Malaysia International Conference on Communications (MICC)*, Kuala Lumpur, 2013, pp. 511-516.
[3] H. Fukuchi and P. Chodkaveekityada, "Propagation impairments along satellite-to-earth path and their mitigation technologies," *2015 IEEE 4th Asia-Pacific Conference on Antennas and Propagation (APCAP)*, Kuta, 2015, pp. 433-434.
[4] Chodkaveekityada P, Fukuchi H. “Prediction model of time diversity using Japan rain radar data,” *International Journal of Satellite Communications and Networking*. 2017 Jul 1;35(4):281-93.

[5] Ng YY, Singh MS, Thiruchelvam V. "Performance analysis of 60-min to 1-min integration time rain rate conversion models in Malaysia,"*Journal of Atmospheric and Solar-Terrestrial Physics*. 2018 Jan 1;167:13-22.
[6] Fabbro V, Castanet L, Croce S, Riva C. "Characterization and modelling of time diversity statistics for satellite communications from 12 to 50 GHz,"*International Journal of Satellite Communications and Networking*. 2009 Mar 1; 27(2):87-101.
[7] E. Matricciani, "Time diversity as a rain attenuation countermeasure in satellite links in the 10-100 GHz frequency bands," *2006 First European Conference on Antennas and Propagation*, Nice, 2006, pp. 1-6.
[8] Matricciani E. "Probability distributions of rain attenuation obtainable with linear combining techniques in space-to-Earth links using time diversity." *International Journal of Satellite Communications and Networking*. 2018 Mar;36(2):220-37.
[9] R. Nakajo and Y. Maekawa, "Characteristics of rain attenuation time variation in Ka band satellite communications for the kind of rain types in each season," *2012 International Symposium on Antennas and Propagation (ISAP)*, Nagoys, 2012, pp. 1473-1476.
[10] Q. W. Pan, J. E. Allnutt and C. Tsui, "Evaluation of Diversity and Power Control Techniques for Satellite Communication Systems in Tropical and Equatorial Rain Climates," in *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 10, pp. 3293-3301, Oct. 2008.
[11] Islam MR, Lwas AK, Habaebi MH. "Site Diversity Gain for Earth-to-Satellite Links Using Rain Intensity Measurement,"*Indonesian Journal of Electrical Engineering and Informatics (IJEEI)*. 2017 Dec 1;5(4):330-8.
[12] A. F. Ismail and P. A. Watson, "Characteristics of fading and fade countermeasures on a satellite-Earth link operating in an equatorial climate, with reference to broadcast applications," in *IEE Proceedings - Microwaves, Antennas and Propagation*, vol. 147, no. 5, pp. 369-373, Oct. 2000.
[13] Arapoglou PD, Panagopoulos AD, Cottis PG. "An analytical prediction model of time diversity performance for earth-space fade mitigation," *International Journal of Antennas and Propagation*. 2008.
[14] H. Y. Lam, L. Luini, J. Din, C. Capsoni and A. D. Panagopoulos, "Performance of SatCom systems implementing time diversity in equatorial Malaysia," *The 8th European Conference on Antennas and Propagation (EuCAP 2014)*, The Hague, 2014, pp. 511-514.
[15] Hodge, D. B. "An improved model for diversity gain on earth-space propagation paths." *Radio Science*. 17, no. 6 (1982): 1393-1399.
[16] Rafiqul, Islam Md, Md Moktarul Alam, Ali Kodhim Lwas, and Sarah Yasmin Mohamad. "Rain Rate Distributions for Microwave Link Design Based on Long Term Measurement in Malaysia." *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*. 2018, 10, no. 3: 1023-1029.
[17] Series P. "Propagation data and prediction methods required for the design of Earth-space telecommunication systems," Recommendation ITU-R. 2015 :618-12.
[18] Rafiqul IM, Lwas AK, Habaebi MH, Alam MM, Chebil J, Mandeep JS, Zyoud A. "Analysis of Time Diversity Gain for Satellite Communication Link Based on Ku-Band Rain Attenuation Data Measured in Malaysia". *International Journal of Electrical and Computer Engineering (IJECE)*. 2018 Aug, 8(4):
[19] Suriza A.Z., Islam Md. Rafiqul, Wajdi Al-Khateeb And A.W.Naji, "Analysis Of Rain Effects On Terrestrial Free Space Optics Based On Data Measured In Tropical Climate", *IIUM Engineering Journal*,Vol 12, No. 5, pp. 45-51, December, 2011.
[20] Hassan Dao, Islam, Md. Rafiqul And Khalid Al-Khateeb, "Modification Of ITU-R Rain Fade Slope Prediction Model Based On Satellite Data Measured At High Elevation Angle", *IIUM Engineering Journal*,Vol 12, No. 5, pp. 53-59, December, 2011.
[21] Md Moktarul Alam, Islam Md. Rafiqul, Khairayu Badron, Farah Dyana A. R., Ali Kadhim Lwas and Hassaan Dao, "Time Diversity Gain Analysis for Earth to Satellite Link Based on Measured Rain Rate", *2018 7th International Conference on Computer and Communication Engineering (ICCCE)*, pp. 109-113, September 19-20, 2018.