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Rain attenuation prediction models for Lagos Island at 17 and 45 Ghz

Abayomi IO Yussuff, Destine O Akinboyewa
Department of Electronic and Computer Engineering, Lagos State University, Lagos, Nigeria

Abstract

This paper investigated the suitability of some popular terrestrial rain attenuation prediction models for Lagos Island, Lagos, Nigeria, at 17 and 45 GHz. At 10 GHz and above, line of sight radio communications is impeded due to the fact that larger raindrops, and is therefore follows that, to effectively model a terrestrial link system in tropical stations, it is necessary to carefully investigate and identify the most suitable model to efficiently and accurately predict rain attenuation exceedances at various percentages of time. Monthly rain data spanning five years (January 2014 to December 2018) were sourced from the Nigerian Meteorological Agency. Four prediction models (ITU-R P.530-17, Da Silva Mello, Crane Global and Moupfouma) were studied. ITU-R P.530-17 model produced the closest predicted values when compared to the measured attenuation values at both 17 and 45 GHz, and it was distantly followed by the Crane Global model. However, at 17 GHz, Moupfouma exhibited the worst performance, while Da Silver Mello showed the worst at 45 GHz, for all percentages of time exceeded. Furthermore, this outcome surmises that the ITU-R P.530-17 model adequately cater for all locations for terrestrial communication links, for temperate, tropical and equatorial alike, for domestic (at p=0.1%) and commercial users (at p=0.01%) of the time exceeded.

Keywords: attenuation, frequency, prediction models, rain rate, terrestrial links

Introduction

Higher microwave frequencies, especially the millimetre wave band is of utmost importance to network service providers and satellite equipment system designers today as a result of the available wider spectrum as well as providing higher data rate capacities for high speed transmission [1]. Absorption and scattering (leading to depolarization) of a microwave radio frequency signal by rain, ice or snow which are most especially common at frequencies above 10 GHz results in attenuation. That is, electromagnetic disturbance of the leading edge of a storm front gives rise to the degradation of a microwave signal. Some of the key factors that influence the cumulative probability distribution of the rainfall attenuation include the effective path length, polarization, frequency of transmission, elevation angle, the antenna tilt angle, height of the station of the mean sea level, and temperature of the antenna amongst others. Although [2] reported that path length and geographic area presents major challenge. However, the spacio-temporal non-homogeneity of rain precipitation should be seen as presenting a much higher challenge.

For instance, a considerable volume of rain precipitation for point-to-point radio communication links in mobile backhaul networks has been reported to result in signal outage of a considerable portion of the network [3]. Also, at 10 GHz and above, line of sight radio communications is impeded due to the fact that larger raindrops are experienced in temperate climatic regions compared to tropical and equatorial climatic regions [4]. It therefore follows that, to effectively model a terrestrial link system in a tropical station like Lagos, Nigeria, the need to carefully investigate and utilize an efficient and accurate prediction methods cannot be overemphasized.

The procedure of rainfall occurrence over a radio link was investigated by [5]. It was found out that the link follows a definite queuing pattern in partial agreement with Markovian queue concept, leading a suggestion that the rain Precipitation nature at equatorial and subtropical climates are quite significantly different from that of the temperate stations. The authors concluded that a good knowledge of rainfall queue theory over microwave links would be useful in developing effective and dynamic rain attenuation mitigation standards in assisting radio communication engineers, as well as providing an improvement to the ITU-R proposed models.

Empirical rain attenuation prediction models are known to be cheaper, faster, portable and easier to deploy than physical models. There are various terrestrial rain attenuation prediction models currently being proposed by researchers globally. However, there is need to carefully study each of them to determine their suitability, especially as it concerns tropical and equatorial stations. Four of such popular rain attenuation prediction models are investigated at both Ku and Ka frequency bands for terrestrial communication links in Lagos Island. They are:

ITU-R P.530-17 prediction model

ITU-R P.530-17 [6] is the current recommendation for estimating long-term statistics of rain attenuation required for the design of terrestrial line-of-sight systems. With rain data of rain rate $R_{0.01}$ exceeded for 0.01% of the time as input, specific attenuation, γ_R (dB/km) for each of the frequencies are computed using ITU-R P.838-3 [7]. Thereafter, the effective path length, d_{eff}, of the link is determined by multiplying the actual path length d by a distance factor r, which is derived as:

$$r = \frac{1}{0.477\, d^{0.633} R_{0.01}^{0.073\alpha} f^{0.123} - 10.579\left[1 - \exp(-0.024d)\right]} \quad (1)$$

Where f is the frequency in GHz and α is the specific attenuation in dB/m.

The path attenuation exceeded for 0.01% of the time is calculated as:

$$A_{0.01} = \gamma_R d_{eff} = \gamma_R dr \text{ dB} \quad (2)$$

For other percentages of time *p* in the range 0.001% to 1%, the following expressions are used:

$$\frac{A_p}{A_{0.01}} = C_1 p^{-(C_2 + C_3 \log_{10} p)} \quad (3)$$

Where $C_1 = (0.07^{C_0})[0.12^{(1-C_0)}]$ (4a)

$$C_2 = 0.855C_0 + 0.546(1 - C_0) \quad (4b)$$

$$C_3 = 0.139C_0 + 0.043(1 - C_0) \quad (4c)$$

Where $C_0 = \begin{cases} 0.12 + 0.4[\log_{10}(f/10)^{0.8}] & f \geq 10 \ GHz \\ 0.12 & f < 10 \ GHz \end{cases}$ (5)

The prediction model procedure is valid in all parts of the world for maximum frequency of 100 GHz and path lengths up to 60 km.

Da Silva Mello prediction model

Da Silva Mello *et al.* [8] proposed a unified method for the prediction of rain attenuation valid for both satellite and terrestrial links and is presented as follow:

$$A_p = k\left[1.763R^{0.753+0.197/L_s \cos\theta} \cos\theta + \frac{203.6}{L_S^{2.455}} R^{0.354+0.088/L_s \cos\theta} \sin\theta\right]^{\alpha} \frac{L_S}{1+\frac{L_s \cos\theta}{119 R^{-0.244}}} \quad (6)$$

For the terrestrial case $L_S = d$, and $\theta = 0$. Hence, equation (6) becomes

$$A_p = k[1.763R^{0.753+0.197/d}]^{\alpha} \frac{d}{1+\frac{d}{119R^{-0.244}}} \quad (7)$$

Where R_{effT} is the effective rain rate for terrestrial links, R is the rain rate $R_{0.01}$, d is the terrestrial path distance and d_0 is the equivalent cell diameter.

Where $R_{effT} = 1.763R^{0.753+0.197/d}$ (8)

And $d_0 = 119.R^{-0.244}$ (9)

Crane Global prediction model

Similar to [8], Crane Global prediction model [9] was formulated for both for terrestrial and slant paths. The model was developed based on data studied for path lengths of 5, 10 and 22.5 km. Crane assumed that to acquire adequate sample size at 22.5 km for point rates in excess of 25 mm/h, the probability of occurrence is independent beyond 10 km. The resulting model is described by:

$$A_T(R,D) = \gamma(R)\left(\frac{e^{y\delta(R)}-1}{y} + \frac{e^{zD}-e^{z\delta(R)}}{z} e^{\alpha\beta}\right) \quad (10)$$

$$\delta(R) < D < 22.5$$

$$A_T(R,D) = \gamma(R)\left(\frac{e^{y\delta(R)}-1}{y}\right), 0 < D < \delta(R) \quad (11)$$

Where A_T is the horizontal path attenuation (dB), *R* is the rain rate (mm/h), *D* is the path length (km) and γ(*R*) is the specific attenuation. Other coefficients are empirical constants of the piecewise exponential model. These are given as:

$$B = \ln(b) = 0.83 - 0.17\ln(R) \quad (12)$$

$$C = 0.026 - 0.03\ln(R) \quad (13)$$

$$\delta(R) = 3.8 - 0.6\ln(R) \quad (14)$$

$$u = \frac{B}{\delta(R)} + C \quad (15)$$

$$y = au \quad (16)$$

$$z = ac \quad (17)$$

Moupfouma prediction model

This model [10] predicts the percentages of time associated to any rain attenuation from a specific rain attenuation made by rain rate $R_{0.01}$ (mm/h) observed on a particular geographical station. The induced attenuation $A_{0.01}$ (dB) exceeded for 0.01% is given by:

$$A_{0.01} = \gamma_{R_{0.01}} \times L_{eq} \quad (18)$$

Where $\gamma_{R_{0.01}} = kR_{0.01}^{\alpha}$ (19)

And $L_{eq}(R_{0.01}, L) = L \times exp\left(\frac{-R_{0.01}}{1+\xi(L)\times R_{0.01}}\right)$ (20)

Given that $\xi(L) = \begin{cases} -100; & for \ L \leq 7 \ km \\ \left(\frac{44.2}{L}\right)^{0.78}; & for \ L > 7 \ km \end{cases}$ (21)

where again, $A_{0.01}$ is the path attenuation (dB) at 0.01% of the time, $R_{0.01}$ is the rainfall rate (mm/h), $\gamma_{R_{0.01}}$ is the specific attenuation, L_{eq} is the equivalent propagation path length, *L* is the actual path length and *ξ* is the adjustment factor. *k* and *α* are parameters governed by radio links operating frequency.

Materials and Methods

Monthly rainfall and measured attenuation data were acquired from the Nigerian Meteorological Agency (NIMET) for a period of five years (January 2014 to December 2018) for Lagos Island and in Lagos, Nigeria. The yearly mean rainfall was obtained for five years. Lagos Island with Geographical coordinates of longitude 3.31 ºE, and latitude of 6.46 ºN had a mean annual rainfall rate of 139.28 mm/hr for the five years. Lagos Island is bordered by the Lagoon.

This paper employed the Chebil and Rahman [11] technique for converting the hourly data to its equivalent one-minute rain rate values. The conversion formulas are given in equations (22) and (23).

$$CF60 = R1(p)/R60(p) \qquad (22)$$

$$CF60 = 0.772p - 0.041 + 1.141 * exp\,(-2.570 * p) \qquad (23)$$

Where $CF60$ is the rain rate conversion factor. It is the ratio of $R1(p)$, which is the rain rates for a given percentage of time, p with an integration time of 1 minute and $R60(p)$, the rain rates for a given percentage of time, p with an integration time of 60 minutes. This conversion method is limited to $0.001\% \leq p \geq 1.0\%$ of the time exceeded. Hence, when the hourly rain rate, $R60(p)$ is known, the one-minute rain rate values, $R1(p)$ can be derived using equation (24).

$$R1(p) = R60(p) \times CF60 \qquad (24)$$

Results and Discussion

At 17 GHz as shown in Figures 1, the ITU-R P.530-17 model overestimated the measured attenuation values from 0.001% to 0.02% of time exceeding with attenuation values from 49.96 dB to 25.66 dB respectively. It nonetheless exhibited the best approximations to the measured attenuation values at 17 GHz.

For instance, it predicted 49.96 dB, 25.66 dB and 9.71 dB at 0.001%, 0.01% and 0.1% of the time respectively against the measured attenuation values of 39.26 dB, 24.82 dB and 12.13 dB at the same percentage of the time. On the other hand, Da Silva Mello, Crane Global and Moupfouma models underestimated the measured attenuation values all through. Displayed in Figure 2 illustrates the attenuation versus rain rate plot for Lagos Island at 17 GHz. The least and highest rain rates are 92.01 and 152.9 mm/hr respectively.

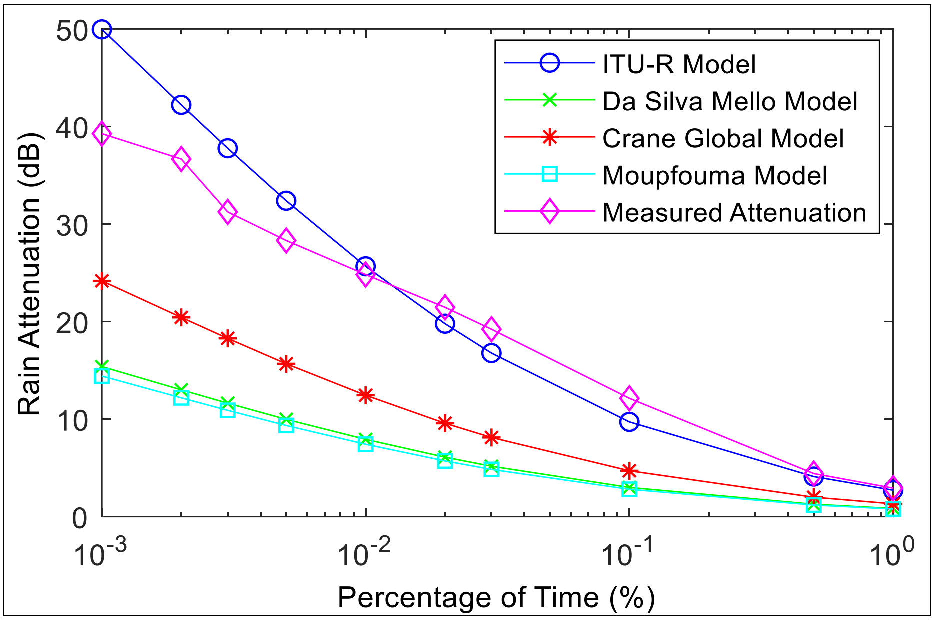

Fig 1: Attenuation against percentage of time for Lagos Island at 17 GHz

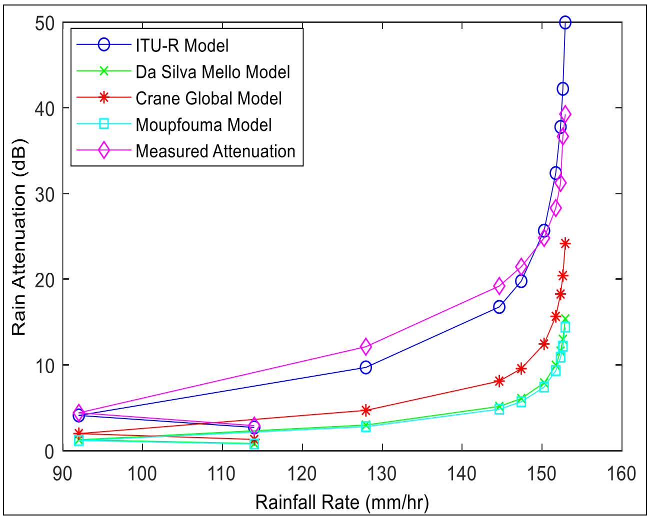

Fig 2: Attenuation versus rain rate for Lagos Island at 17 GHz

The statistical errors computations for Lagos Island at 17 GHz is presented on Table 1. From the RMS (root mean square) error, it is observed that the ITU-R P.530-17 recommended rain attenuation prediction model showed the least error values; hence it is the best suitable model.

At 45 GHz (Figures 3), ITU-R P.530-17 model intercepted the measurement at 0.1% and then overestimated the measured attenuation values at other percentages of time from 138.09 dB to 28.35 dB respectively. Furthermore, it 138.09 dB, 75.54 dB and 28.35 dB at 0.001%, 0.01% and 0.1% of the time respectively against the measured attenuation values of 131.28 dB, 62.16 dB and 30.41dB at the same percentage of the time. Again, Da Silva Mello, Crane Global and Moupfouma models underestimated the measured attenuation values from 0.001% to 1% of time exceeded.

Thus, the ITU-R P.530-17 presented the best performance at 45 GHz.

Table 1: Comparison of Mean Error, Standard Deviation & Root Mean Square for Lagos Island at 17 GHz.

Parameters	Models	0.001	0.002	0.003	0.005	0.01	0.02	0.03	0.1	0.5	1
Mean Errors	ITU-R P.530-17	0.0052	0.0146	0.0134	0.0214	0.0215	0.0173	0.0129	-0.0063	-0.0402	-0.0539
	Da Silva Mello	-0.0884	-0.0874	-0.0869	-0.0866	-0.0866	-0.0871	-0.0875	-0.0897	-0.0934	-0.0949
	Crane Global	-0.0617	-0.0533	-0.0569	-0.0558	-0.0557	-0.0573	-0.0589	-0.066	-0.0782	-0.0832
	Moupfouma	-0.0697	-0.067	-0.0658	-0.065	-0.0649	-0.0662	-0.0674	-0.0731	-0.0327	-0.0867
Standard Der.	ITU-R P.530-17	0.025	0.021	0.0177	0.014	0.0133	0.0138	0.0221	0.0246	0.031	0.0475
	Da Silva Mello	0.0094	0.0165	0.0136	0.02	0.0202	0.018	0.0154	0.0121	0.0287	0.0333
	Crane Global	0.0166	0.0262	0.0291	0.0311	0.0313	0.0283	0.0247	0.0168	0.0451	0.0533
	Moupfouma	0.0149	0.0243	0.0272	0.0292	0.0294	0.0264	0.0229	0.0165	0.0421	0.0494
RMS	ITU-R P.530-17	0.0245	0.0151	0.0052	0.0161	0.0166	0.0075	0.013	0.0237	0.0503	0.0718
	Da Silva Mello	0.0879	0.0358	0.0349	0.0343	0.0342	0.0852	0.0362	0.0905	0.0977	0.1006
	Crane Global	0.0594	0.0521	0.0438	0.0463	0.046	0.0493	0.0534	0.0631	0.0903	0.0988
	Moupfouma	0.063	0.0624	0.0599	0.0581	0.0579	0.0607	0.0634	0.0749	0.0923	0.0998

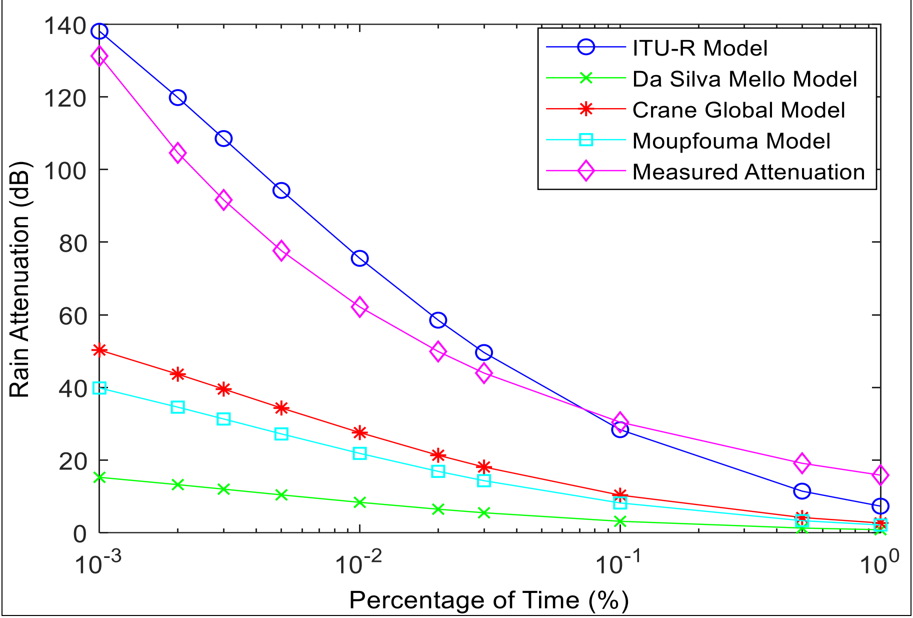

Fig 3: Attenuation against percentage of time for Lagos Island at 45GHz

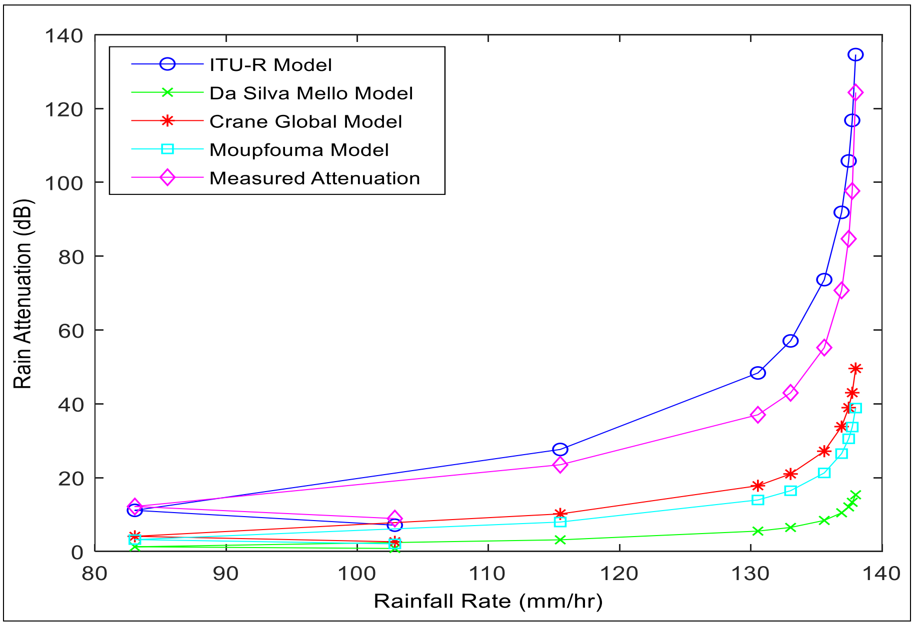

Fig 4: Attenuation versus rain rate for Lagos Island at 45GHz

Figure 4 illustrates the attenuation versus rain rate plot for Lagos Island at 45 GHz. The lowest rain rate is 83.04 mm/hr, while the highest is 139.28 mm/hr. Again, from Table 2, similar to what was observed for the 17 GHz Ku frequency band, the the ITU-R P.530-17 recommended rain attenuation prediction model is the best compared with the four models under study.

Table 2: Comparison of Mean Error, Standard Deviation & Root Mean Square for Lagos Island at 45 GHz

Parameters	Models	0.001	0.002	0.003	0.0IB	0.01	0.02	0.03	0.1	OS	1
Mean Errors	1TU-R P.530-17	0.0052	0.0146	0.0134	0.0214	0.0215	0.0173	0.013	-0.0068	-0.0402	-0.0539
	Da Silva M ello	-0.0384	-0.0874	-0.0869	-0.0866	-0.0366	-0.03-1	.0 0375	-0.0897	-0.0934	-0.0949
	Crane Global	-0.0617	-0.0583	-0.0569	-0.0558	-0.0557	-0.05-5	.0 0589	-0.066	-0.0782	-0.0832
	Moup fouma	-0.0697	-0.067	-0.0658	-0.065	-0.0649	-0.0662	-.0674	-0.0731	-0.0827	-0.0867
Standard Dev.	ITU-R P.530-17	0.025	0.021	0.0177	0.01:	0.0138	0.0188	0.0221	0.0246	0.031	0.0475
	Da Silva M ello	0.0094	0.0165	0.0186	0.02	0.0202	0.013	0.0154	0.0121	0.0287	0.0333
	Crane Global	0.0166	0.0262	0.0291	0.0311	0.0313	0.0233	0.0247	0.0168	0.0451	0.0533
	Moup fouma	0.0149	0.0243	0.0272	0.0292	0.0294	0.0264	0.0229	0.0165	0.0421	0.0494
RMS	ITU-R P.530-17	0.0245	0.0151	0.0052	0.0161	0.0166	0.0075	0.018	0.0237	0.0508	0.0713
	Da Silva M ello	0.0879	0.0858	0.0849	0 0.33	0.0342	0.0852	0.0862	0.0905	0.0977	0.1006
	Crane Global	0.0594	0.0521	0.0483	0 r.:6S	0.046	0.0498	0.0534	0.0631	0.0903	0.0988
	Moup fouma	0.068	0.0624	0.0599	0.0581	0.0579	0.0607	0.0634	0.0749	0.0928	0.0998

Conclusions

In this study, four empirical rain attenuation prediction models for terrestrial communication links 17GHz and 45GHz spanning five years were assessed and analysed, for Lagos Island in Lagos, Nigeria. Empirical prediction models are generally acknowledged to be cheaper, faster, portable and easier to deploy compared to physical models. More so, there are various terrestrial rain attenuation prediction models currently being proposed by researchers worldwide. Hence, the need to carefully investigate some of the widely recognized ones in order to determine their suitability or otherwise, cannot be overemphasized. Four of such popular rain attenuation prediction models are investigated at both 17 and 45 GHz. Results obtained from the study revealed that ITU-R P.530-17 model produced the closest predicted values when compared to the measured attenuation values at both 17 and 45 GHz, followed by Crane model. However, at 17 GHz, Moupfouma exhibited the worst performance, while Da Silver Mello showed the worst at 45 GHz. To sum up, it can be firmly concluded that the ITU-R P.530-17 prediction model is the most suitable for predicting rain attenuation for Lagos Island, which is a tropical, station with attendant high rainfall rates. This will assist in ensuring the design of reliable (in terms of availability and quality of service) terrestrial communication link during rain events.

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