EARTH-SKY LINK QUALITY PERFORMANCE FOR FIXED AND MOBILE SCENARIOS IN TROPICAL REGIONS

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Abstract—Recent advances in satellite communication technologies in the tropical regions have led to significant increase in the demand for services and applications that require high channel quality for fixed and mobile satellite terminals. Due to lack of reliable investigations regarding accurate performance evaluation, experiments, and analysis on the satellite communication link in tropical regions under atmospheric impairments for both scenarios, accurate signal quality performance analysis is necessary. This paper presents the link characteristics observations and performance analysis with propagation measurements done in tropical region to provide an accurate database regarding rain attenuation in the tropics for fixed and mobile scenarios. The paper also presents a newly developed extension attached to the measurements setup for improved packet error rate (PER) performance evaluation related to the degradations occur in channel quality for different types of impairments (rain, mobility, and physical obstacles) for 4 modulation schemes, namely QPSK, 8-PSK, 16-QAM and 32-QAM. The results show that the rain impairments at Ku band cause up to $12.5\,\text{dB}$ and $23\,\text{dB}$ at $77.5°$ and $40.1°$ elevation angles respectively in two tropical regions inside Malaysia for fixed scenario with a significant increase in PER at higher M-ary modulation schemes. For mobile scenario the PER appeared at higher M-ary scheme due to the lower signal power degradation in which, in turn, exceeded $1\,\text{dB}$ when the vehicle speed exceed $100\,\text{km/hr}$

at clear sky. The obstacles at the satellite communication link are shown to have significant effect on the power and PER received by satellite terminal especially at higher M-ary modulation schemes.

1. INTRODUCTION

As signal propagates through the medium between the satellite and Earth stations, it suffers from impairments that may occur according to different obstacles that absorb, scatter, or even block the signal energy, such as shadowing due to physical objects (primarily by buildings or trees), rain, and clouds. The amount of losses depends on several parameters, particularly the transmission parameters (such as frequency, elevation angle, and modulation scheme), the Earth station mobility and position parameters, and the atmospheric parameters (such as rain rate and rain height).

Due to lack of reliable performance analysis in tropical regions [1–3] and to identify the effects of these impairments on the signal quality level in terms of packet error rate (PER), this paper presents a newly developed error rate software (ERS) extension to improve the satellite/Earth station quality performance assessment and analyzes regarding the effects of the above mentioned parameters. This analysis is associated with the new measurement database provided worldwide for fixed and mobile scenarios in the tropics.

The transmission parameters' effect on the signal quality performance for fixed and mobile scenarios will be presented in Section 2 with the link topology scenarios. The atmospheric effects will be presented in Section 2.1, along with the ERS block design process for fixed scenario. And then the mobility effects will be presented in Section 2.2 with ERS block for mobile scenario.

2. METHODOLOGY

Transmission parameters significantly affect the performance evaluation of the quality of service (QoS) of the signal. In particular, the frequency and elevation angle present effects that should be identified by satellite system designers prior to the design process.

According to Friis transmission equation, the frequency is directly proportional to the signal power attenuation and, hence, to the carrier-to-noise ratio, which could also lead to the increase in the error rates. For lower frequencies, below 3 GHz, the ionospheric scintillation significantly affects the signal quality. This effect starts to disappear as the frequency increases above that value [4]. Moreover, raindrops in the link between the satellite and Earth station exert a paramount

effect on the quality of the signal at higher frequencies, particularly above 10 GHz [5]. Figure 1 shows the attenuation variation for different frequency values we calculated in Selangor, Malaysia for 0.01% of the time exceedance, using the International Telecommunication Union (ITU) prediction model [6, 7] which has been proven to be an acceptable prediction model for rain attenuation calculations in tropical regions [8–10].

Figure 1 clearly shows that the elevation angle also considerably affects the signal. Under the same environment parameters, if the Earth station in Selangor is connected to MEASAT 3/3A at 11.6 GHz transmission frequency at an elevation angle of 77.5°, the attenuation is approximately 16 dB, whereas it reaches to approximately 26 dB if it is connected to SUPERBIRD C2 with an elevation angle of 41.1° and to 61 dB if it is connected to INTLESAT 19 with an elevation angle of 17.4°.
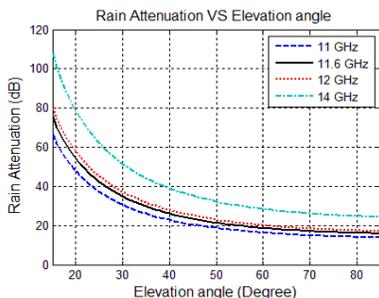
Figure 1. Rain attenuation as a function of frequency and elevation angle variations for 0.01% of time exceedance.
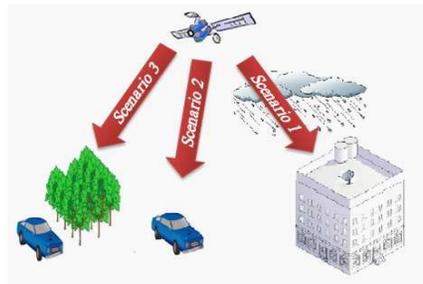
Figure 2. Satellite/Earth station communication links.

To extract and analyze the atmospheric losses as well as the mobility effects out of the other impairments, several experiments were conducted, which considered fixed and mobile scenarios. Three scenarios considered in this study involved a broadcasting geostationary satellite linked to fixed or mobile Earth station(s) at Ku band as shown in Figure 2.

2.1. Error Rates for Fixed Scenario

In satellite communications, several impairments can cause significant degradation in the signal quality in fixed Earth station scenario, such as transmission parameters' variations and atmospheric impairments. Rainfall exerts paramount effect on the received signal power at Ku

band. Raindrops absorb and scatter signal energy depending on the drop size, density, and shape [11]. Tropical regions usually have convective rainfall because of their more severe weather condition periods and larger raindrop size compared with those in the temperate regions [1, 3, 12, 13]. This special impairment increases the need to investigate the quality performance in tropical regions in terms of the error rates as appropriate indicators. The PER can be calculated theoretically using four modulation schemes, namely, QPSK, 8-PSK, 16-QAM, and 32-QAM. These modulation schemes are widely used in satellite communication systems.

Error bits inside the packets are distributed in correlational manner; therefore, they cannot be calculated accurately. When the error bit distributions inside the packets are identical and independent, the following equation can calculate the approximate PER:

$$\text{PER} = 1 - (1 - \text{BER})^{L_p} \tag{1}$$

where BER is the bit error rate and L_p the packet length. However, Equation (1) is not accurate in high-order QAM constellations, and the bits are usually distributed in a correlational manner [14]. Therefore, the improved PER calculation for M-QAM scheme for gray mapping, was expressed by Equation (2) [14].

$$\text{PER} = 1 - \prod_{a=1}^{\log_2 I} [1 - P_I(a)]^{L_p/[\log_2(I \times J)]} \times \prod_{b=1}^{\log_2 J} [1 - P_J(b)]^{L_p/[\log_2(I \times J)]} \tag{2}$$

where

$$P_I(a) = \frac{1}{I} \times \sum_{n=0}^{I(1-2^{-a})-1} \left\{ (-1)^{\left\lfloor \left(n \times 2^{(a-1)}/I\right) \right\rfloor} \times \left[2^{(a-1)} - \left\lfloor 0.5 + \frac{n \times 2^{(a-1)}}{I} \right\rfloor \right] \right.$$
$$\left. \times \text{erfc} \left(\sqrt{\frac{3 \log_2(I \times J) \times \text{EbNR}}{I^2 + J^2 - 2}} \times (2a + 1) \right) \right\} \tag{3}$$

and,

$$P_J(b) = \frac{1}{J} \times \sum_{m=0}^{J(1-2^{-b})-1} \left\{ (-1)^{\left\lfloor \left(m \times 2^{(b-1)}/J\right) \right\rfloor} \times \left[2^{(b-1)} - \left\lfloor 0.5 + \frac{m \times 2^{(b-1)}}{J} \right\rfloor \right] \right.$$
$$\left. \times \text{erfc} \left(\sqrt{\frac{3 \log_2(I \times J) \times \text{EbNR}}{I^2 + J^2 - 2}} \times (2b + 1) \right) \right\} \tag{4}$$

EbNR is the bit energy-to-noise ratio, which can be calculated by the following equation:

$$\text{EbNR} = \text{CNR} - \text{SR} + \text{BW} \tag{5}$$

Using the Friis transmission equation, EbNR will be

$$\text{EbNR} = \text{EIRP} + G_r - 20 \log \left(\frac{4\pi d}{\lambda} \right) - L_A - L_S - N_o - \text{SR} \qquad (6)$$

where EIRP is the effective isotropic radiated power, and G_r, L_A, L_s, N_o and SR are the receiver gain, atmospheric losses, system losses, noise spectral density, and symbol rate, respectively. The term $(4\pi d/\lambda)$ is the free-space loss that depends on the link length (d) and the transmitted frequency. In the case of $I = J$, the PER can be calculated by

$$\text{PER} = 1 - 2 \times \prod_{a=1}^{\log_2 I} \left[1 - \frac{1}{I} \times \sum_{n=0}^{I(1-2^{-a})-1} \left\{ \left[2^{(a-1)} - \left\lfloor 0.5 + \frac{n \times 2^{(a-1)}}{I} \right\rfloor \right] \right. \right.$$
$$\left. \left. \times \text{erfc} \left(\sqrt{\frac{3 \log_2(M) \times \text{EbNR}}{2M - 2}} \times (2a + 1) \right) \right\}^{L_p/[\log_2(M)]} \right] \qquad (7)$$

Combining Equations (6) and (7) yields a new equation that obtains the PER according to the rain attenuation values, as expressed in Equation (8). This equation can be used to investigate the exact PER for the satellite-tropical region communication link.

$$\text{PER} = 1 - 2 \times \prod_{a=1}^{\log_2 I} \left[1 - \frac{1}{I} \times \sum_{n=0}^{I(1-2^{-a})-1} \left\{ \left[2^{(a-1)} - \left\lfloor 0.5 + \frac{n \times 2^{(a-1)}}{I} \right\rfloor \right] \right. \right.$$
$$\left. \left. \times \text{erfc} \left(\sqrt{\frac{3 \log_2(M) \times [\text{CNR}_{CS} - L_A - \text{SR}]}{2M - 2}} \times (2a + 1) \right) \right\}^{L_p/[\log_2(M)]} \right] \qquad (8)$$

where the clear sky carrier to noise ratio $\text{CNR}_{CS} = \text{EIRP} + G_r - 20 \log(\frac{4\pi d}{\lambda}) - L_S - N_o$.

2.2. Error Rates for Mobile Scenario

With the development in satellite communication technology and its applications, the quality of services has become an essential requirement for mobile users. The quality of these services suffers from the several impairments mentioned in Section 2.1, as well as from mobility impairments such as the shadowing caused by roadside trees or buildings, multipath effect (primarily caused by mountains or nearby buildings), Doppler effect (which depends on the speed and direction of the movement), and antenna tracking error. These four major causes of signal degradation prompt the satellite communication system designers to build well-formulated models to predict the QoS

performance during mobile scenarios, such as the ITU model [15]. PER can also be calculated from the actual measured attenuation data using Equation (9), which is a modification of Equation (8), the modification was related to the mobility impairments.

$$
\begin{aligned}
\text{PER} = 1 - 2 \times \prod_{a=1}^{\log_2 I} \left[1 - \frac{1}{I} \times \sum_{n=0}^{I(1-2^{-a})-1} \left\{ \left[2^{(a-1)} - \left\lfloor 0.5 + \frac{n \times 2^{(a-1)}}{I} \right\rfloor \right] \right. \right. \\
\left. \left. \times \text{erfc} \left(\sqrt{\frac{3\log_2(M) \times [\text{CNR}_{CS} - L_M - \text{SR}]}{2M - 2}} \times (2a + 1) \right) \right\} \right]^{L/[\log_2(M)]}
\end{aligned} \tag{9}
$$

where L_M is the mobility impairments expressed in decibels.

3. EXPERIMENTAL SETUP

To observe the actual signal power performance under atmospheric and mobility impairments, three experimental processes were performed concerning the scenarios shown in Figure 2. The first scenario deals with the measurement of the atmospheric impairments on a fixed node. The second scenario deals with the mobility impairments on mobile nodes moving with different speeds. The third scenario deals with the mobility impairments on mobile nodes moving with constant speed under link obstacle.

3.1. Experimental Setup for Atmospheric Impairments

In this category, the experiments were done in two different regions in the tropics, namely, Selangor and Penang in the middle and southeast of Malaysia, respectively.

In Selangor, we measured the attenuation of the signal power in decibels at the engineering campus in UPM university ($3.01°$N latitude, $101.6°$E longitude, and $95\,$m altitude above sea level) on January 23, 2013, and then computed the PER using Equation (8). We used a $65\,$cm reflector antenna to detect the signals transmitted from MEASAT 3/3A at $91.5°$E with an elevation angle of $77.5°$ in the frequency range from $10.75\,$GHz to $11.75\,$GHz. Then, the $11.6\,$GHz signal was selected for analysis. The measurement setup is shown in Figure 3.

After the signals were reflected from the reflector antenna, they passed through the low-noise box (LNB) processes, namely, filtration, amplification, and down conversion to L-band frequencies using a $9.75\,$GHz local oscillator. The received signals then passed through a splitter prior to the decoder for detection and to the spectrum analyzers
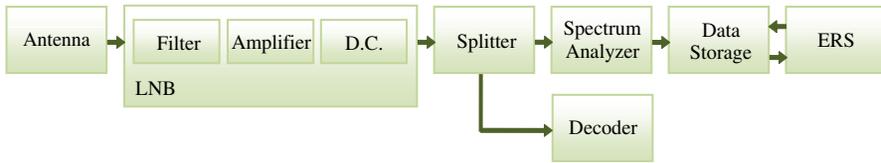
Figure 3. Measurement setup for stationary-node scenario.

for data recognition and analysis. The output data were stored in a PC and input to the newly designed ERS to obtain the PER of the received measured signal.

Moreover, the raw data from the experimental measurements done in Penang were obtained, and a one-day measurement (January 25, 2010) was retrieved from the series of measurements taken between 2002 and 2010 [8, 16, 17] at the engineering campus in USM university (5.17°N latitude, 100.4°E longitude, and 57 m altitude above sea level). A 2.4 m reflector antenna was used as part of the measurement setup, which is similar to the one shown in Figure 3 except for the last block — the ERS block — which we added at the moment to obtain the PER of the 12.2 GHz signal transmitted from SUPERBIRD C2 (144°E) at an elevation angle of 40.1°. The spectrum analyzer sweep time in both experiments was 1 sec, and the mean value was calculated every minute. 1000 bit packet length was assumed in this experiment.

The rainfall rate has been measured in mm for both mentioned tropical regions (Selangor and Penang) in conjunction with the experiments, these data then converted to mm/hr to provide clear representation of the rain induced attenuation.

3.2. Experimental Setup for Mobility Impairments

To identify the error rates for the mobile scenario, we conducted several experiments considering the cases of quality degradation of signals received by a receiver mounted in a car driven at different speeds in Serdang, Selangor, Malaysia. These cases are listed as follows:

Case 1: The node moved at different speeds up to 150 km/hr. The received signal at zero speed (stationary) was also measured using the same mobile antenna system.

Case 2: The node moved at constant speed (40 km/hr) under link obstacles, namely tall trees (approximately 12 m tall, and 7 m — away from the car — in average) at the roads ides and bridges.

For the measurement setup, we used a 0.44 m mobile antenna system mounted at the roof of a car. The mobile antenna system, pointed at MEASAT 3/3A 91.5°E, had a high tracking speed (75°/sec)

to reduce the tracking error as much as possible. The antenna system performed several principal functions, namely detection, filtering, amplification, and down conversion to L-band intermediate frequency (IF) using a 9.75 GHz local oscillator. The measurement setup is shown in Figure 4. To the best of our knowledge, this is the first mobility experiment done to obtain the signal quality under the above mentioned cases for satellite communication in tropical regions.
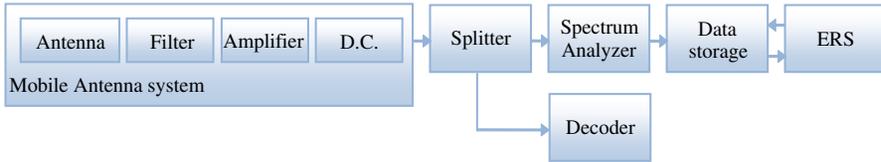
Figure 4. Measurement setup for the mobile scenario.

As the signals were received by the mobile antenna system, they passed through the four aforementioned processes and then split into two directions; one went to the decoder and the other to the spectrum analyzer for data recognition and analysis. These data were stored before and after being input to the ERS for error rate calculation 1000 bit packet length was assumed in both cases.

4. RESULTS AND DISCUSSION

As mentioned earlier, the rain parameters, such as rain height, rainfall rate, droplet size, and shape, along with the link parameters such as elevation angle and transmitted frequency, result in major effects on the satellite communication link that influence its performance metrics such as attenuation and PER. Figure 5 shows the measured rainfall rate and rain attenuation as a loss in the received signal power.

The effective rain started at minute No. 1076 (5:56 PM) and reached the heavy rain level after 6 min, with maximum attenuation of approximately 12.5 dB. The rainfall rate started to decrease at minute No. 1122 (6:42 PM) to the other rainfall rate levels until minute No. 1181 (7:41 PM) when the rain stopped.

The 40 min heavy rain reflected its influence on the satellite received signal power and caused approximately 12 dB to 12.5 dB attenuation, whereas the heavy rain effect on the signal power in Penang caused attenuation of approximately 23 dB (Figure 6) within the 63 min of rain period (from 11:40 AM to 12:43 PM).

The difference in the attenuation level during the heavy rain was mainly due to the variation in the elevation angle, which had a
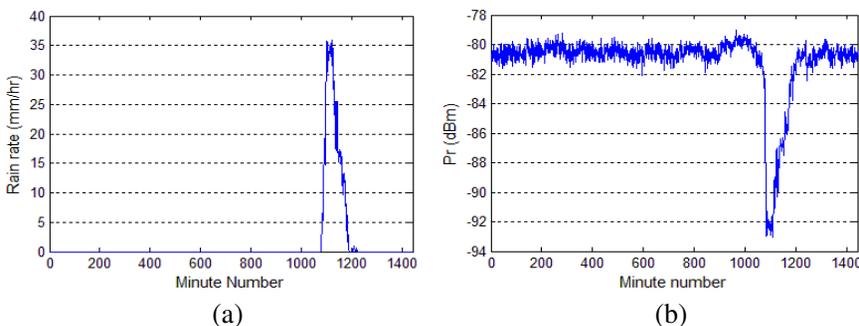
Figure 5. Time-series measurements in Selangor. (a) Rain rate. (b) Received power.
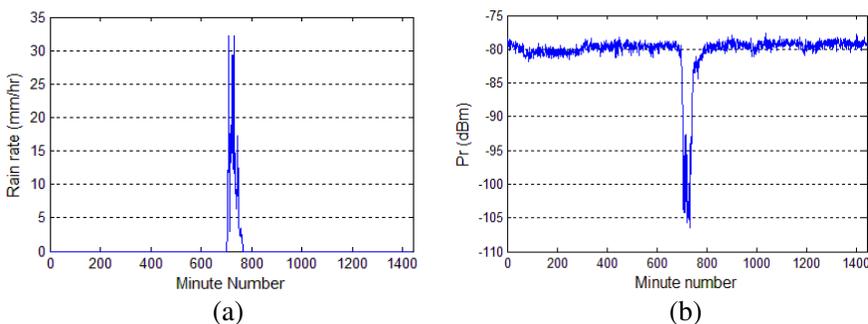
Figure 6. Time-series measurements in Penang. (a) Rain rate. (b) Received power.

difference of 37.4°; hence, the link passed through a longer rainy path in space, as mentioned in Section 3. This attenuation caused losses in the received data and, thus, affected the QoS.

For the mobile scenario, several cases were considered in the measurement presented in Section 3.2 to obtain reliable performance evaluation of the signal received by the mobile receiver attached to a vehicle. As explained earlier, movement of the communication link destination with respect to the source causes additional degradation to the signal quality level. Figure 7 shows that the attenuation increased slightly when the car speed increased. The attenuation increased by approximately 0.6 dB when the car moved at 60 km/hr speed. When it attained 80 km/hr speed, the attenuation slope changed, and the attenuation level tended to increase more slightly than that below the 80 km/hr speed. Hence, the losses reached to approximately 1 dB at
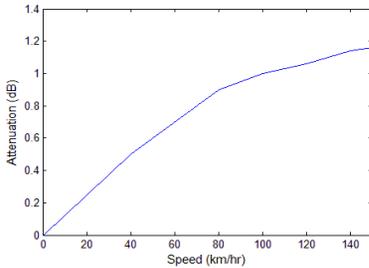
Figure 7. Attenuation measurement under different vehicle speeds.
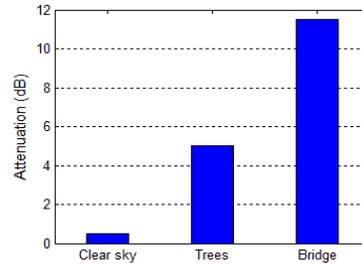
Figure 8. Mobile scenario at speed 40 km/hr under different link obstacles.

100 km/hr, 1.15 dB at 140 km/hr, and 1.18 dB at 150 km/hr.

In reality, as the car moves on the road, it may experience shadowing or blocking in the communication link for some periods of time mainly due to the trees at the sides of the road or bridges where the vehicle passes under, which can cause additional loss in the signal quality. We made several experiments with the car moving at 40 km/hr speed under tall trees (approximately 12 m average tall) at both sides of the road. The results showed that these trees caused additional 4.5 dB average attenuation compared with that under the clear-sky case, as shown in Figure 8.

The last set of measurement was made in the case where the vehicle passed under bridges at a speed of 40 km/hr. The signal suffered significant loss in the communication link; the attenuation reached approximately 11 dB compared with that under the clear-sky mobile scenario.

The above-mentioned causes of attenuation (rain, mobility, and obstacles) affected the signal quality and hence reduced the number of successfully received data packets. The PER is one of the main matrices in evaluating the QoS and can be obtained using the developed ERS mentioned in Sections 2 and 3. The ERS calculates the PER of the measured signal using the four principal modulation schemes used in recent satellite communication technologies, namely, QPSK, 8-PSK, 16-QAM, and 32-QAM.

Figure 9(a) shows the output of the ERS for the rainy period shown in Figure 5, which shows that under 8-PSK, the PER increased only during the heavy-rain rate period. It fluctuated around 10^{-6}, whereas it fluctuated at 10^{-2} and $10^{-0.5}$ during heavy rain under 16-QAM and 32-QAM, respectively. The PER decreased as the rain rate decreased.

As a result, the PER increased to more than 10^{-10} for 33 min during that day in Selangor under the 8-PSK modulation scheme, as shown in Figure 9(b), and reached approximately $10^{-4.5}$ at the peak rain rate period, which caused serious problems in the communication link for approximately 3 min in that particular day. These problems occurred for 33 min and 47 min during the rainy periods under the 16-QAM and 32-QAM schemes, respectively. However, the link could suffer from disconnection at higher PER of over 20 min/day for higher M-ary modulation schemes, whereas in the QPSK scheme, no significant PER occurred at any time in the day under this case.

However, for the Penang-SUPERBIRD C2 communication link, the rain path length was longer compared with that of the Selangor-MEASAT 3/3A [6]. Therefore, the rain attenuation and packet loss were higher, especially during heavy rain periods. In this case, the PER for the QPSK modulation was significant during heavy rain rates, as
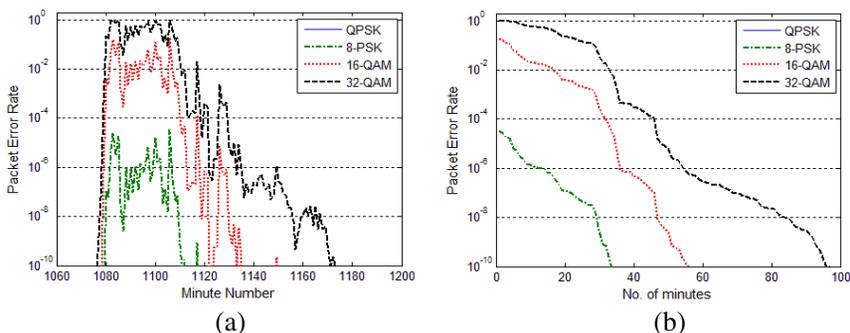
Figure 9. PER during rainy periods in Selangor.
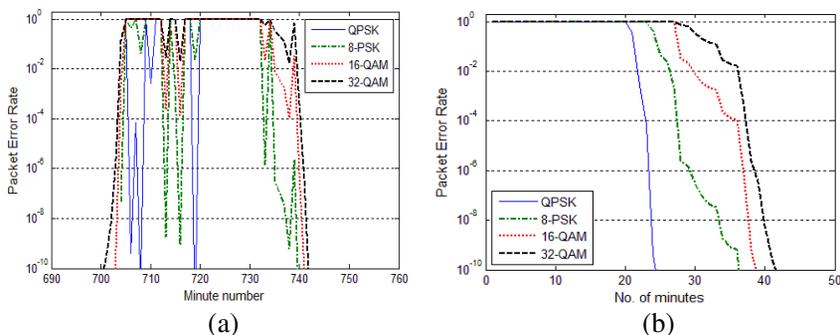
Figure 10. PER during rainy periods in Penang.

shown in Figure 10(a). The major rain effect occurred for $23\,\text{min/day}$ under QPSK, whereas it reached 27, 36, and $38\,\text{min/day}$ under the 8-PSK, 16-QAM, and 32-QAM schemes, as shown in Figure 10(b). The PER attained a higher level that caused blocking of data under all the mentioned modulation schemes for about $20\,\text{min/day}$.

For the mobile scenario, the PER was obtained by the ERS at different vehicle speeds. The amount of losses was not significant, and the PER occurred only under the 32-QAM scheme, as shown in Figure 11. The PERs were below 10^{-11} for the normal- and high-speeds ranges, whereas they exceeded 10^{-11} at the very high speed ranges ($140\,\text{km/hr}$ to $150\,\text{km/hr}$). The effect of mobility at different car speeds under the clear-sky scenario disappeared using lower M-ary modulation schemes.

Obstacles bring another paramount effect by decreasing the signal quality under mobile scenario mainly due to trees and bridges. These obstacles could cause shadowing or even blocking of the signal information. The developed ERS extension calculated the PER caused by these obstacles under several cases. The ERS output shows that trees significantly affect PER performance under the 32-QAM scheme, as shown in Figure 12. The PER due to trees when the car is moving at a speed of $40\,\text{km/hr}$ reached $10^{-6.5}$, whereas it had no considerable effect under lower M-ary modulation schemes.
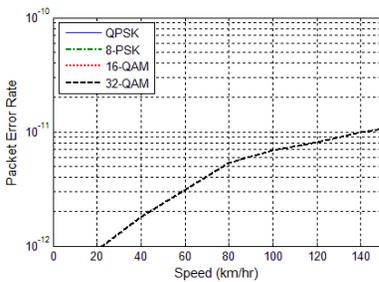
Figure 11. PER for different vehicle speeds.
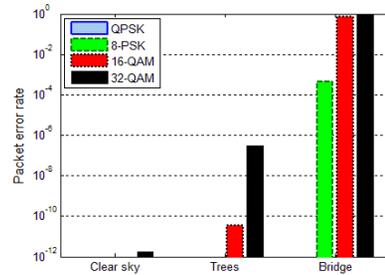
Figure 12. PER for mobile scenario at speed $40\,\text{km/hr}$ under different link obstacles.

However, when the car moved at the same speed under bridges, significant decrease in the signal quality and PER occurred. The ERS calculated the average PER value of the several experiments. Complete blocking of transmission data occurred when the car was under the bridge even for small crossing period under the 32-QAM and 16-QAM schemes, whereas a higher PER was reached under the 8-PSK modulation scheme.

5. CONCLUSION

This paper has presented several experiments conducted in Malaysia to measure the paramount causes of the decrease in channel quality for fixed and mobile scenarios at Ku band, which is the mostly used channel frequency band for communication satellites in the tropics. The communication link characteristics in tropical regions have been explained, and the experimental setup for the fixed and mobile scenarios had been discussed using the newly developed ERS extension to improve the PER calculation under satellite communication link impairments. Rain significantly affected the signal quality, and it caused the attenuation to increase up to 12.5 dB during heavy rainfall at high elevation angle (77.5°). It reached up to 23 dB at lower elevation angle (40.1°) because of the longer rainy path. This rain attenuation value caused high PER that resulted in serious problems to the communication link during heavy rain periods, especially in the Penang-SUPERBIRD C2 link, where the value reached 1 for more than 20 min/day out of the 63 min/day rainy period. This rate value reached 1 under 32-QAM only during heavy rain for just 5 min/day out of the 105 min/day rainy period in the Selangor-MEASAT 3/3a link; however, the PER reached a high value of more than 30 min/day under higher M-ary modulation schemes.

In addition, the measurements recorded the effects of several mobility experimental situations on the quality of received signal. The change in vehicle speed caused small signal power loss that exceeded 1 dB as the car exceeded 100 km/hr under the 32-QAM scheme due to the tracking error and Doppler phenomena. Consequently, the ERS recorded low PER that reached 10^{-1} at 140 km/hr vehicle speed. The speed variations also had a negligible effect under lower M-ary modulation schemes.

Obstacles have significant effect in the tropics on satellite communication link. The link quality encountered serious problem that caused signal unavailability under higher M-ary schemes when the vehicle passed under bridges, whereas the trees caused high PER only for higher M-ary schemes during clear sky, which went higher during rainy periods. The performance evaluation of the paramount reasons for the signal quality degradation was measured and analyzed with an evaluation enhancement using the newly developed ERS extension to increase the quantitative and qualitative information database of the satellite signal performance under link impairments in tropical regions.

ACKNOWLEDGMENT

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