Rain Fade Estimations for the X-Band Satellite Communication Link in the Tropics

A. C. M. Nuroddin, A. F. Ismail, K. Abdullah, K. Badron, M. Ismail, and W. Hashim

Abstract—The X-band satellite communication (satcom) has been conventionally set aside for military and government organizations. It is also commonly known as the military band. The attributes of an X-band satcom hardware are expected to be designed specifically for military operations and they are expected to differ very much to those of commercial frequencies. The satcom will be likely to be exclusively designed to support smaller, low powered, tactical terminals deployed across various theatres of operation. In addition, X-band link is also anticipated to offer a more substantial increased of system capacity due to its higher frequencies compared to the forerunner S-band and C-band. The X-band satcom technology is drawing growing interest from military users including of the Malaysian authorities. However, there are many aspects of X-band that are harder to realize than of those of at lower frequencies. X-band frequencies certainly have higher atmospheric propagation losses, higher RF losses, and certainly much severe signal degradation due to rain. It is would be in the best interest of the satellite designers and engineers alike to accurately appraise the challenges of an X-band satcom link especially in the case of tropical regions where heavy rains are copious whilst the required technological advancements are in pursuit.

Index Terms—Rain attenuation, satcom, tropical region, X-band.

I. INTRODUCTION

The X-band is a subdivision of the microwave radio region of the electromagnetic spectrum. In the instance such as in communication engineering, the frequency range of X-band is rather broadly set at approximately between 7.0 to 11 gigahertz (GHz). X-band satcom are now commonly employed by leading nations as part of the integral set up of their mission critical communications where loss of communications is not an option [1]. In almost all cases, besides the requirement to strategically dimension the terminals’ physical size, the X-band satcom is also specifically designed to operate with high performance in remote and harsh locations that has no access to traditional telephony infrastructure; including naval and maritime platforms. The Malaysian government intends to immediately acquire X-band satellite capabilities to enhance the Malaysian Armed Forces’ communication network [2]. The facilities are considered vital, particularly in ensuring transmission and reception of secured confidential information from military warfare assets distributed strategically across various landscapes.

In designing the new satellite links, the performance predictions of the satellite are vital step to ensure the reliability of the systems. It is very critical to be capable to predict accurately and encountered the impairment of the given link in order to devise the services efficiently. The predicted value of signal loss and fading are commonly utilized in the process of establish the satellite design parameters [3]. Performance is usually expressed as the expected quality of the channel for a very high percentage of time (at least a month and usually a year). For satellite systems, that level achieved is commonly what is called “clear sky”.

Instances of design parameter are the power requirements of the equipment, the antenna characteristics and the service range or the hop distance. These design parameters can be ascertained and from them the performance of a service is stipulated for a particular percentage of the time. The performance can be specified for instance, at availability of 99% of time at a given receiving locality or at a specified percentage of locations within a reception area. Availability is the ratio typically associated with the percentage of the total time a service is enabled or being used, or is available to be utilized during a given interval to the length of the interval.

In satellite communication terminologies, the link availability is usually defined as a percentage of a year when the link will perform as per the required Bit Error Rate (BER). In the case of 99% availability for a year, it states that the link will be accessible for 867.24 hours and unavailable for 87.6 hours (8760 – 867.24 hours / 8760 hours x 100). Equally important, other designation such as the level of interfering signals exceeded for some small percentage of the time, for
instance at 0.1%, also need to be forecasted, again at the reception point or location of concern. Predictions are employed in order to know whether a satisfactory service will be provided at the involved reception point or area and also for spectrum allocation to avoid mutual interference with other systems occupying the same frequency band.

II. TROPICAL RAIN FADE ESTIMATIONS

Radiowave propagation prediction assumes a very significant part in the links design and eventually determines performance of space communication systems. The X-band allotment plan for Malaysia according the International Telecommunications Union (ITU) Appendix 30B includes assignment of frequency bands as high as 8.4 GHz. The operation of high frequency such as X-band encounters the existence of stronger electromagnetic interference concerning the radio signals and atmospheric hydrometeors especially for communication and broadcast purposes [4]. These instances will without doubt disfigure the performance of such high frequency satellite communication systems. Several models have been recommended for predicting rain induced attenuation statistics. Among presently available prediction procedures are the models recommended by the Radiocommunications sector of the International Telecommunication Union (ITU-R) [5], the Dissanayake, Allnutt and Haidara (DAH) rain induced attenuation model [6], the Crane-Global model [7] and the Crane-Two Component model [8].

III. ESTIMATION PROCEDURES

Diverse propagation parameters are required in planning of Earth-space systems operation in either the Earth-to-space or space-to-Earth direction, have to be predicted reliably. For a probable future satellite-Earth link to be operating in Johor Bahru, one of the cities in the southern part of Malaysia, the theoretical assessments of its performance had been deliberated methodically using the following procedures.

The subsequent write-up highlights and involves
adaptations of the ITU-R P.618-10 for the sake of readability and clarity. In the latest version of ITU-R prediction method, the vertical structure of rain is taken into account by the use of an effective rain height $h_R$, obtained from experimental data, in the expression of $L_s$. For vertical paths, the effective path length corresponds to the effective rain height, which at any latitude may diverge from the $0^\circ$C isotherm height $h_{t0}$, as indicated in ITU-R Recommendation, P.839-3 - ‘Rain Height Model for Prediction Methods’ [11]. Numerous methods have been proposed by previous researchers in order to take into account the vertical structure variability of rain. Few of these techniques can be regarded as an extension of those previously developed for terrestrial paths [12]. Whereas some had proposed rain height determination based on investigation on the rain structure itself [13]. Malaysian researchers had conducted preliminary investigation at various local locations using the Tropical Rainfall Measuring Mission (TRRM) satellite and meteorology radars in the hope to identify the actual effective rain height [14] and [15]. The rainfall rates $R_{0.01}$ at time exceedance of 0.01% from the new climatic zone map of ITU-R Recommendation P.837-6 that equals to 100 mm hr$^{-1}$ was utilized in estimating predicted attenuation values [16].

1) Computation of the elevation angle $\theta$, for the Earth-space link:

$$\theta = \tan^{-1}\left[\frac{\cos(l_{G1} - l_{G}) \cos(\phi) - 0.45}{\sqrt{1 - \cos^2(l_{G1} - l_{G}) \cos(\phi)}}\right] (1)$$

Calculation of the polarization angle $\tau$:

$$\tau = \tan^{-1}\left[\frac{\sin|l_{G1} - l_{G}|}{\tan \phi}\right] (2)$$

2) The effective rain height, $h_R$, for the latitude of the station $\phi$ was established according to ITU-R recommendation:

$$h_R = h_{t0} + 0.36km (3)$$

The ITU-R Recommendation P.839-3 outlines that $h_{t0}$ for Malaysia equals to 4.5 km

1) For $\theta \geq 5^\circ$ calculation of the slant-path length $L_s$, below the rain height is as follows:

$$L_s = \frac{(h_R - h_{t0})}{\sin \theta} (4)$$

2) Computation of the horizontal projection, $L_G$, of the slant-path length from:

$$L_G = L_s \cos \theta (5)$$

3) Calculation of the $k$ and $\alpha$ values using the frequency-dependent coefficients, $k_{H1}$, $k_{V1}$, $\alpha_{H1}$, and $\alpha_{V1}$ from Table I of the ITU-R P.838-3.

Based on postulation of spherical drops, values of $k$ and $\alpha$ have been determined at various frequencies between 1 GHz to 1000 GHz for several drop temperatures and drop size distributions. The calculations were carried out by presuming oblate spheroidal drops, aligned with a vertical symmetry axis and with dimensions related to equal volume spherical drops. Values of $k$ and $\alpha$ coefficients based on the Laws and Parson’s rain drop size distribution and a drop temperature of $20^\circ$C have also been determined and incorporated in Table I of Recommendation ITU-R P.838-3[17]. The table also comprises other values for horizontal and vertical polarization of $k$ and $\alpha$ at various frequencies.

Values of $k$ and $\alpha$ at frequencies other than those in the table can be approximated by interpolation using logarithmic scale for frequency $f$, a logarithmic scale for $k$, and a linear scale for $\alpha$. For linear and circular polarization, and for all path geometries, the $k$ and $\alpha$ coefficients for the specific attenuation equation can be determined from using the following equations:

$$k = \left[k_H + k_V + (k_H k_V) \cos^2 \theta \cos 2\tau\right]/2 (6)$$

$$\alpha = \left[k_H \alpha_H + k_V \alpha_V + (k_H \alpha_H k_V \alpha_V) \cos^2 \theta \cos 2\tau\right]/2k (7)$$

where $\theta$ is the path elevation angle and $\tau$ is the polarization tilt angle in relation to the horizontal as in (2) ($\tau = 45^\circ$ for circular polarization).

1) The specific attenuation, $\gamma_R$, using the frequency-dependent coefficients determined above and the rainfall rate, $R_{0.01}$ was acquired by using (1).

Investigators [18] have reported that the relationship between specific attenuation ‘$A$’ or ‘$\gamma_R$’ and rainfall rate $R$ can be estimated by using the power-law.

$$\gamma_R = k(R_{0.01})^\alpha (8)$$

2) Determination of the horizontal reduction factor, $r_{0.01}$, for 0.01% of the time:

$$r_{0.01} = \frac{1}{1 + 0.78 \sqrt{\frac{L_G \gamma_R}{f} - 0.38(1-e^{-2L_G\gamma_R})}} (9)$$

3) Computation of the vertical adjustment factor, $\nu_{0.01}$, for 0.01% of the time:

$$\zeta = \tan^{-1}\left(\frac{h_R - h_{t0}}{L_G r_{0.01}}\right) (10)$$

Since the $\zeta > 0$, therefore the reduced length $L_R$ was calculated according to:

$$L_R = \frac{L_G r_{0.01}}{\cos \theta} (11)$$

In the case of Malaysia, its $\phi < 36^\circ$, hence

$$\chi = 36 - |\phi| (12)$$
\[ V_{0.01} = \frac{1}{1 + \sqrt{\sin \theta \left( 31 \left( 1 - e^{-(b / (1.25 f \gamma_r)^2)} \right) \sqrt{L_v} \gamma_r - 0.45 \right)}} \]  

(13)

1) Determination of the effective path length is:

\[ L_E = L_v V_{0.01} \]  

(14)

2) The anticipated attenuation exceeded for 0.01% of an average year is then determined using:

\[ A_{0.01} = \gamma_r \cdot L_E \]  

(15)

where the effective path length \( L_E \) is the resultant of slant path length, horizontal path reduction factor \( r_{0.01} \) and vertical path reduction factor \( V_{0.01} \). The empirical expression of (15) is then employed for scaling of other time percentage, in order to provide a comprehensive prediction of rain induced attenuation distribution.

3) The predicted attenuation at other time percentages of an average year, in the range from 0.001% up to 1%, is inferred from value in step 11 above; in keeping with the following conditions:

For \( p < 1\% \) and \( |\varphi| < 36^\circ \) and \( \theta \geq 25^\circ \):

\[ \beta = -0.005|\varphi| - 36 \]  

(16)

and the estimated attenuation is:

\[ A_p = A_{0.01} \left(\frac{p}{0.01}\right)^{(0.655 + 0.033ln(p) - 0.045ln(A_{0.01}) - \beta(1 - p)\sin \theta)} \]  

(17)

Table II itemizes the parameters determine in accordance to the ITU-R’s recommendations.

<table>
<thead>
<tr>
<th>TABLE II: CALCULATED PARAMETERS USING ITU-R RECOMMENDATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>( R_{0.01} ) (mm hr(^{-1})): ITU-R P.837-6</td>
</tr>
<tr>
<td>( \theta ) ((^\circ))</td>
</tr>
<tr>
<td>( \tau ) ((^\circ))</td>
</tr>
<tr>
<td>( h_r ) (km): ITU-R P.839-3</td>
</tr>
<tr>
<td>( L_v ) (km)</td>
</tr>
<tr>
<td>( L_c ) (km)</td>
</tr>
<tr>
<td>( k_p ): ITU-R P.838-3</td>
</tr>
<tr>
<td>( K_r ): ITU-R P.838-3</td>
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<tr>
<td>( \alpha_0 ): ITU-R P.838-3</td>
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<td>( \alpha_0 ): ITU-R P.838-3</td>
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<td>( \alpha )</td>
</tr>
<tr>
<td>( K )</td>
</tr>
<tr>
<td>( \gamma_\alpha ) (dB)</td>
</tr>
<tr>
<td>( r_{0.01} ) (mm hr(^{-1}))</td>
</tr>
<tr>
<td>( \xi ) ((^\circ))</td>
</tr>
<tr>
<td>( \chi ) ((^\circ))</td>
</tr>
<tr>
<td>( v_{0.01} ) (mm hr(^{-1}))</td>
</tr>
<tr>
<td>( L_g ) (km)</td>
</tr>
<tr>
<td>( A_{0.01} ) (dB)</td>
</tr>
<tr>
<td>( \beta )</td>
</tr>
</tbody>
</table>

IV. FINDINGS AND OBSERVATIONS

In planning communications links, cumulative distributions may be the most applicable presentation format for the long-term data. For example, link availability or exceedance at a point can be established from its annual cumulative distribution. Accordingly, suitable rain induced attenuation margins can be identified which to be incorporated into the system in the effort to attain the desired link performance. The predicted rain fade estimation using ITU-R recommendation as well as incorporation of local data [15] and [19] namely the rain height of 5.4 km as well as rainfall rate of 164 mm hr\(^{-1}\) can be viewed in Fig. 4.

**TABLE III: SELECTED TIME PERCENTAGES AND PREDICTED VALUES**

<table>
<thead>
<tr>
<th>Time exceedance (%)</th>
<th>ITU-R Predicted Attenuation (dB)</th>
<th>ITU-R with local data Predicted Attenuation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000</td>
<td>0.45</td>
<td>0.70</td>
</tr>
<tr>
<td>0.100</td>
<td>2.88</td>
<td>4.30</td>
</tr>
<tr>
<td>0.010</td>
<td>6.50</td>
<td>9.35</td>
</tr>
<tr>
<td>0.001</td>
<td>9.94</td>
<td>13.78</td>
</tr>
</tbody>
</table>

Table III catalogues certain projected attenuation values for the likely future X-band satellite-Earth link in Malaysia. Preliminary results of possible rain induced-attenuation signal degradation to be experienced by an X-band link at Johor Bahru were produced. These initial outcomes suggested that due to the severity of the rain induced attenuation that will be confronted, the X-band satellite operation in Malaysia and others in tropical region may not be easily achievable to operate at 99.99% availability (equivalent to 0.01% time exceedance) to concur with the strict communication QoS requirement. Considerable substantial margin by today’s technological advancement of somewhat more than 9 dB; has to be incorporated into the wireless communication link in order to cope with rain fading in such severe climate.

If X-band satellite communications is to be actually implemented, current and forthcoming studies should be immediately dedicated on identifying integrated solutions in the satellite’s design i.e. transmission power level management, determination of appropriate reflector size, antennas configuration, radiating antenna technologies, steerable beam capability, etc. RF engineers can participate in the effort by exploring the use of one or more fading mitigation techniques to lessen the effect of rain induced attenuation.
V. CONCLUSION

The use of X-band satcom will be materialized in Malaysia for the next few years. The X-band satcom facilities will be special digital communication means for the government or armed authorities to transmit a high data, sounds and videos between the receiving and transmitting antennas. In anticipation of the evolution towards the X-band for high data rate multimedia applications, among the main constraints of concern will be the rain fade. Initial studies on propagation impairment have identified that consequence is indeed be quite severe Malaysian climate i.e. tropical climates, so standard performances are expected be taxing to achieve in these regions. Production of predicted impairment statistics as been highlighted in this paper is therefore may be central and need to be taken into serious consideration in the future design and deployment of anticipated high frequencies satcom systems in the tropics.

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A. C. M. Nuroddin graduated top of the 2012 B.Eng in Communication Engineering class at the International Islamic University Malaysia. She is currently a research assistant whilst pursuing her MSc candidacy at the Electrical and Computer Engineering department, IIUM. Her research interests include wireless communication devices and Cognitive Radio applications. He is a registered Professional Engineer with Board of Engineering Malaysia and also a Senior Member of the IEEE.

A. F. Ismail is a lecturer at the Department of Electrical and Computer Engineering, Faculty of Engineering, IIUM. He completed his bachelor degree studies in Electrical Engineering at Gannon University, Pennsylvania, USA with Cum Laude Latin honors. He holds MSc from University of Essex, UK and PhD from University of Bath, UK. His research interests include millimeter and microwave propagation studies and Cognitive Radio applications. He is a registered Professional Engineer with Board of Engineering Malaysia and also a Senior Member of the IEEE.

K. Abdullah obtained his BSc in Electrical Eng. from University of Ohio USA in 1997 and completed his ME in Electrical Eng. at Universiti Teknologi Malaysia in 2003. He received PhD in Electrical and Computer Eng from RMIT University, Melbourne, Australia. He is an assistant professor at faculty of Engineering, International Islamic University Malaysia. His research interests are in the area of Cognitive Radio as well as advance modulation design. He is a Senior Member of IEEE and member of IEM.

M. Ismail is the Malaysian National Space Agency director. He directs the satellite ground operation as well as the spacecraft testing facilities. He was the principal engineer for Malaysian Remote Sensing Satellites – RazakSAT and TiungSAT. Maszlan received his BEng and MSc from the National University of Malaysia specializing in wireless and satellite communication. He is one of the committee members of IEEE Malaysian chapter and Asia-Pacific Regional Space Agency Forum.

W. Hashim received his bachelor degree in Information Technology, Business Management and Language from University of York, UK in 1999. She then pursued her MSc in Multimedia Technology at University of Bath, UK in 2001. She completed her PhD studies from King’s College London, UK in 2008 in the field of Telecommunication Engineering. She is currently a staff researcher at the Wireless Communication Cluster, MIMOS Berhad with focus in cognitive radio, WLAN, OFDM, space-time coding, MIMO systems and wireless system.