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Rain Attenuation And Link Budget Design For Ku Band Downlink Signal In Ghana

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Abstract: Good signal reception depends on a reliable communication link. But as the signal travels through the communication medium, several factors affect the quality of the signal at the receiver. In Ku band digital satellite transmission, rain is the major cause of signal impairment. The ITU-R rain rate and attenuation models are globally accepted models in determining the rain rate and attenuation at various locations worldwide, in the absence of locally measured 1-minute data recommended for rain attenuation studies. In this paper, we used the ITU-R rain rate and attenuation model to determine the rain rate and attenuation for 22 synoptic stations in Ghana. Knowledge of rain attenuation for a given location can be used to develop a link budget design. A link budget design was therefore developed for various climatic zones in Ghana for a Ku band downlink frequency using some assumptions. As Ghana migrates from analogue to digital satellite television broadcasting, it is important for some preliminary work to be undertaken to determine the attenuation levels the signals are likely to suffer. This will serve as a tool for system designers and manufacturers of satellite equipment for Ghana.

Key words: rain rate, rain attenuation, signal impairment, link budget.

INTRODUCTION

The International Telecommunication Union (ITU) at its Geneva 2006 convention advocated for all countries to migrate from analogue to digital television broadcasting. This is because of the enormous advantage in satellite services provided by higher frequency bands. Also, consumers demand high speed broadband services which cannot be satisfied by existing lower frequency bands due to congestion and bandwidth limitations. Most countries have completed the migration process but Ghana is yet to accomplish this after missing the deadline on a number of occasions. Signals propagated through higher frequencies (above 10 GHz) are adversely affected by rain leading to low quality and less availability of the signal at the receiver. Rain drops absorb and scatter radio waves resulting in insufficient power at the receiver to allow for proper decoding of data at an acceptable bit error rate. This affects the signal availability and dependability objectives. The severity of rain impairments increases with frequency and varies with regional locations (Ajayi, 1996). Since rain was established to be the major cause of signal attenuation at Ku band and due to the varying nature of rainfall across locations, many researchers have conducted experiments in their climatic regions to measure the rain rate and attenuation. These studies have been carried out mostly in the temperate regions. But the severity of rain effect on the signal, are more pronounce at the tropics and equatorial regions where intense rainfall events are common as compared to the temperate regions. This is reported in the work of Ajayi (1996), Moupfouma (1985) and Ojo and Omotosho (2013). Satellite system design requires as input 1-minute rain rate data with various exceedance probabilities. Based on this many researchers have conducted experiments on their local climatological regions to measure 1-minute rain rate and attenuation. In regions where there are enough data coverage, prediction models have been proposed. But there is a lack of 1-minute integration time rain rate data across the world, especially in developing countries like Ghana. The International Telecommunication Union Recommendation (ITU-R P. 837-6, 2012) has provided global maps, where data can be extrapolated based on some data from regions where they are available, mostly the temperate regions. This situation is caused by the limited availability of 1-minute integration time rain rate data from tropical and equatorial countries for modeling and testing of prediction models (Ojo et al, 2009). Knowledge of 1-minute rain rate is essential in radio communication system design. In this paper as Ghana is migrating from analogue to digital television broadcasting and rain will be the major cause of signal impairment, it will be prudent to determine the rain rate values for Ghana. The applicability of the global models in the Ghanaian tropical environment is also unknown. However, since ITU-R rain rate and attenuation model is the most globally accepted model for predicting rain rate and attenuation at any location, we applied the ITU-R model in the 22 synoptic stations in Ghana. Satellite communication engineers are concerned with determining the factors required for optimal link availability and quality of performance. To some extent, consumers of satellite technology also require the signal to be available for most part of the year. A link budget analysis of the signal is therefore important in order to quantify the loss the signal is likely to encounter in a particular climatic condition. The 22 synoptic stations in Ghana will therefore be divided into four climatic zones. The average attenuation will be determined for each climatic zone and a link budget design developed accordingly with some assumptions. This will give an idea of the transmission losses and its impact on consumers in such climatic zones in Ghana.

THE GHANAIAN TROPICAL CLIMATE

Ghana is located on latitude 7.9465 °N and longitude 1.0232 °W in Sub-Saharan Africa. The climate of Ghana has two main seasons; the wet and dry seasons. Northern Ghana experiences its rainy seasons from May to mid-October while Southern Ghana experiences its rainy season from March to mid-November. In the Southern part of Ghana, there is a bi-modal rainy season: April through June and September through November. The agro-ecological zones in Ghana is divided into four main zones by the Ghana Meteorological Agency (Owusu and Waylen, 2009). These zones are the Forest Zone (Abetifi, Akim Oda, Axim, Ho, Koforidua, Kumasi, Akatsi and Takoradi), the Coastal Zone (Accra, Ada, Akatsi, Saltpond and Tema), the Transition Zone (Kete-Krachie, Sunyani , Kintampo and Wenchi) and Northern Zone (Bole, Navrongo, Tamale, Wa and Yendi). The forest zone covers the tropical forest and the south western coast of the country. The Coastal zone covers the dry coastal strip of South western Ghana. The transition zone also covers the middle part of Ghana whiles the Northern zone covers the northern part of the Country, which experiences similar rainfall totals as that of the other zones , but has a single wet season. Figure 1 shows a map of the 22 synoptic stations and the agro-ecological zones in Ghana.

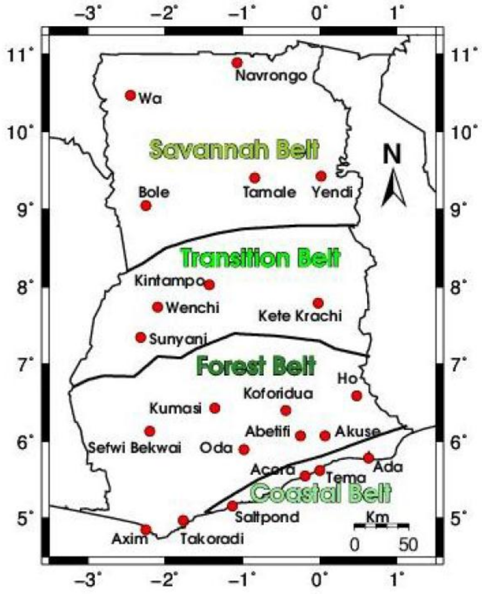

Figure 1. *Synoptic stations of Ghana: Source (Manzanas et al.2014)*

The 22 synoptic stations will therefore be classified into four climatic zones for the purpose of this study. Northen Zone (Navrongo, Wa, Tamale, Bole, Yendi), Middle zone (Kumasi, Sunyani, Sefwi-Bekwai, Wenchi, Kete-Krachi, Abetifi), Southern zone (Akuse, Ho, Koforidua, Akim-Oda, Akatsi), Coastal zone (Accra, Tema, Axim, Saltpond, Ada-Foah , Takoradi). Each climatic Zone consist of at least five stations. The 22 stations are well distributed across the country.

ITU-R RAIN RATE AND ATTENUATION MODEL

The most internationally accepted and widely used model for the prediction of rain rate is the ITU-R rain rate model. It is based on this reason we decided to apply it to the Ghanaian tropical climate. ITU-R recommendation P.837-6 (2012) contains annexes and maps of meteorological parameters that have been obtained using the European Centre for Medium-Range Weather Forecast (ECMWF) ERA-40 re-analysis database, which are recommended for the prediction of rainfall rate statistics with 1-minute integration time, when local measurements are not available. The model uses a database of parameters ($P_r 6, Mt \ and \ \beta$), available from the ITU's 3M Group (2008), each of which is matched to a pair of longitude and latitude. This model was also used to determine 1-munite rain rate for 22 synoptic stations in Ghana for comparison with Moupfouma prediction. For the prediction of rain attenuation, the ITU-R rain attenuation model (ITU-R P.618-11, 2013) was selected. This is because the ITU-R model is widely accepted and recommended as the standard model for predicting rain attenuation globally. It has been reported that the ITU rain attenuation prediction model results were close to the average prediction of a set of results obtained from the application of eight different methodologies (Emiliani et al.,2009; Ojo et al.,2008,2009). The following are the input parameters needed for the model: point rainfall rate for the location for 0.01% of an average year (mm/h), height above sea level of the earth station (km), elevation angle, latitude of the earth station (deg), frequency (GHz) and effective radius of earth (8500 km). The detailed step-by-step procedures can be found in the Appendix A of this study. The equations are captured in A1 to A12. The geostationary satellite chosen for this study is Intelsat 17 (IS-17) located 066.04 °E with its service footprint at different angles to each station. A Ku band downlink frequency of 11.812 GHZ was measured by a spectrum analyzer and used for this study. The results of the rain rate and attenuation are presented in Table 1.

LINK ANALYSIS

Link analysis relates the transmit power and the receive power and shows in detail how the difference between the two are accounted for. Some basic transmission parameters such as antenna gain, free space path loss, frequency and the basic link power equation are discussed. The concept of system noise and how it is quantified on the transmission link is then developed. Other parameters such as noise power, noise temperature are defined. The carrier-to-noise ratio and related parameters used to define communication link design and performance are discussed. The flux density and link equation can be used to calculate the power received by an earth station from a satellite transmitter with output power P_t watts and a lossless antenna with gain G_t, the flux in the direction of the antenna bore sight at a distance R meters in given by:

$$(pfd)_r = \frac{p_t\, g_t}{4\pi\, r^2} \quad {}^{W}\!/_{m^2} \qquad (1)$$

$p_t\, g_t$ is the Effective Isotropic Radiated Power (EIRP) because an isotropic radiator with an equivalent power equal to $p_t\, g_t$ would produce the same flux density is all directions. The power flux density expressed in dB, will be

$$(PFD)_r = 10\log\left(\frac{p_t g_t}{4\pi r^2}\right) \qquad (2)$$

$$(PFD)_r = EIRP - 20\log(r) - 10.99 \qquad (3)$$

For an ideal receiving antenna with an aperture area of A m^2would collect a power of P_r watts given by

$$P_r = (PFD)_r A = \frac{P_t\, G_t A}{4\pi\, R^2} \ [Watts] \qquad (4)$$

Since an isotropic radiator with an equivalent power equal to $p_t\, g_t$ would produce the same flux density in all directions. The received ideal antenna gain is given by:

$$G_r = \frac{4\pi A}{\lambda^2}, A = \frac{G_r \lambda^2}{4\pi} \quad (5)$$

Thus

$$P_r = \frac{P_t G_t G_r}{(4\pi R/\lambda)^2} \quad (6)$$

Equation (6) is known as the link equation and it is essential in the calculation of power received in any radio link. The term $(4\pi R/\lambda)^2$ is known as the Free Space Loss (L_{FS}). It accounts for the dispersion of energy as an electromagnetic wave travels from a transmitting source. For a real antenna, however, the physical aperture area A_r, the effective aperture area A_e and the aperture efficiency η_A are related by the equation (7)

$$A_e = \eta_A A_r \quad (7)$$

For real antenna equations (4) and (6) becomes (8) and (9)

$$P_r = \frac{P_t\, G_t \eta_A A_r}{4\pi\, R^2} = \frac{P_t\, G_t A_e}{4\pi\, R^2} [Watts] \quad (8)$$

$$G_r = \frac{4\pi \eta_A A_r}{\lambda^2} = \frac{4\pi A_e}{\lambda^2} \quad (9)$$

The link equation expressed in equation (6) can be rewritten as equation (10)

$$Power\ received = \frac{EIRP\ x\ Received\ antenna\ gain}{Free\ Space\ Loss} [Watts] \quad (10)$$

Using decibel notations, equation (10) can be simplified as :

$$P_r = EIRP + G_r - L_{FS}\, [dBW] \quad (11)$$

where

$EIRP = 10\log(P_t G_t)\, [dBW]$

$G_r = 10\log(4\pi A_e/\lambda^2)\, [dB]$

$L_{FS} = 20\log\left(\frac{4\pi R}{\lambda}\right) [dB]$

For completeness we define the losses on the link by two components, the free space loss and all other losses ,ℓ_o, defined as

$$\ell_o = \sum(Other\ Losses) \quad (12)$$

The free space loss component of equation (11) is the algebraic sum of the free space loss and other loss components such as: losses in the atmosphere due to attenuation by air, water vapor and rain, losses at the antenna at each side of the link and possible reduction in antenna gain due to antenna misalignment or from hardware elements such as antenna feeds, line losses , etc.

Thus, equation (11) can be rewritten as (13)

$$P_r = EIRP + G_r - (L_{FS} + \textstyle\sum \ell_o)\ [dBW] \quad (13)$$

Noise temperature provides a way of determining how much thermal noise active and passive devices generate in the receiving system. The most important source of noise in the receiver is thermal noise in the pre-amplification stage. The noise power at the receiver antenna terminals is given by the Nyquist equation as (14)

$$n_r = kt_s b_N\ watts \quad (14)$$

Where

k = Boltzmann's Constant

= $1.39x10^{-23}$ Joules/K = -198 dBm/K/Hz = -228.6 dBw/K/Hz

t_s = equivalent noise temperature of the noise source, in Kelvin

b_N = noise bandwidth, in Hz

One of the objectives of any satellite communication system is to meet a minimum carrier to noise (C/N) ratio for a specified percentage of time. The (c/n) can be expressed in terms of the eirp, (G/T) and other llink parameters developed earlier. Thus a link with transmit power p_t , transmit antenna gain, g_t, and receiver antenna gain, g_r as shown in figure 2

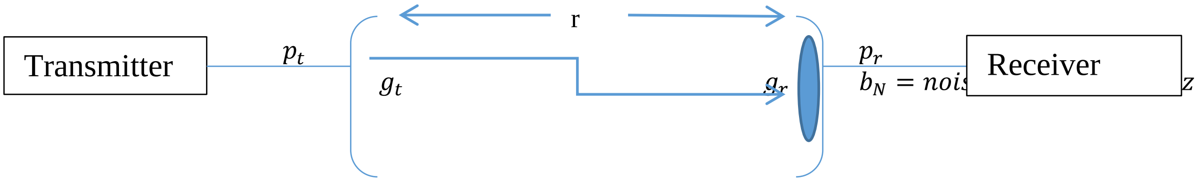

Figure 2 *Satellite Link parameters*

The power at the receiver antenna terminals, p_r, is found as

$$p_r = p_t g_t g_r \left(\frac{1}{\ell_{FS}\ell_o}\right) \quad (15)$$

The carrier-to-noise ratio at the receiver terminals is then

$$\left(\frac{c}{n}\right) = \frac{p_r}{n_r} = \frac{p_t g_t g_r \left[\frac{1}{\ell_{FS}\ell_o}\right]}{kt_s b_N} \quad (16)$$

Or

$$\frac{c}{n} = \frac{(eirp)}{kb_N}\left(\frac{g_r}{t_s}\right)\left(\frac{1}{\ell_{FS}\ell_o}\right) \quad (17)$$

Expressed in dB,

$$\left(\frac{C}{N}\right) = EIRP + \left(\frac{G}{T}\right) - (L_{FS} + \textstyle\sum Other\ Losses) - k - B_N \quad (18)$$

Where the EIRP is in dBw, the bandwidth B_N, is in dBHz, and k=-228.6 dBw/K/Hz.

The larger the $\left(\frac{C}{N}\right)$, the better the link will perform. Most communication links require a minimum $\left(\frac{C}{N}\right)$ value of 6 to 10 dB for acceptable performance.

RESULTS

In order to measure the received power or C/N ratio at the receiver, some system parameters must be considered. In this paper, the C/N ratio for a downlink Ku band signal is determined for the various climatic zones using equation

(18). It is assumed that all receiver dishes point to the same satellite for all locations. The satellite is INTELSAT-17 situated at 066.04 °E on a geosynchronous orbit. Table 2 shows some local parameters used for the study based on INTELSAT 17. A downlink frequency of 11.812 was measured using a spectrum analyzer. The value of the EIRP from the satellite for receivers in Ghana is 52.5 dBW. The antenna gain, assuming a 60 % efficiency is 34.47 dBi. The noise bandwidth and Boltzmann's constant are 88.65 dBHz and -228.6 dBW/K/Hz respectively. The free space loss in calculated using frequency and distance. The other loss component is the average of the attenuation value for the climatic zone. All other loss component are held constant. Tables 3, 4, 5 and 6 gives a summary of the link design parameters used to obtain the C/N values for the various climatic zone. Table 7 shows a generalized one for Ghana.

***Table 1** ITU-R rain rate and attenuation values for 0.01% of time.*

STATIONS	ITU-R Rain Rate (mm/h)	ITU-R Attenuation (dB)
NAVRONGO	49.8792	19.0804
WA	53.9679	21.8904
TAMALE	50.4067	19.8029
BOLE	53.1707	22.4479
YENDI	51.8200	20.4363
KUMASI	64.6355	24.0583
SUNYANI	62.9224	26.2475
SEFWI- BEKWAI	71.9832	27.62477
WENCHI	60.1910	24.5551
KETE-KRACHI	59.7351	21.4627
ABETIFI	67.4187	25.2808
AKUSE	74.3556	25.8871
HO	65.8095	24.7831
KOFORIDUA	74.8765	25.9816
AKIM-ODA	69.5637	25.6115
AKATSI	74.8765	24.8183
ACCRA	79.9807	26.3613
AXIM	84.4658	29.8303
TEMA	79.8906	28.7759
SALTPOND	77.2589	28.4459
ADA-FOAH	79.9235	25.5304
TAKORADI	82.8924	28.9223

***Table 2** Some local geometry parameters used for the study based on Intelsat 17 (IS-17) Geostationary Satellite*

ZONE	STATION	LATITUDE	DISH ELEVATION ANGLE (°)	STATION HEIGHT (m)	γ_R (dB/km)	L_E (km)
NORTHERN	NAVRONGO	10.54N	14.305	213.4	1.9977	9.5513
	WA	10.03N	14.211	322.7	2.3402	9.3539
	TAMALE	09.33N	14.462	168.8	1.9998	9.9026
	BOLE	09.02N	14.262	299.5	2.3584	9.5183
	YENDI	09.27N	14.319	195.2	2.0821	9.8151
MIDDLE	KUMASI	06.43N	13.843	286.3	2.6595	9.0462
	SUNYANI	07.20N	13.064	308.8	2.5803	10.1722
	SEFWI-BEKWAI	06.12N	13.911	170.8	3.0028	9.1996
	WENCHI	07.45N	13.45	338.9	2.4551	10.0015

	KETE-KRACHI	07.49N	14.812	122	2.4366	8.8085
	ABETIFI	06.40N	13.542	594.7	2.8049	9.0129
SOUTHERN	AKUSE	6.06N	15.345	17.4	3.1365	7.9985
	HO	6.36N	15.99	157.6	2.7193	8.0106
	KOFORIDUA	6.06N	15.217	166.5	3.1468	8.0341
	AKIM-ODA	5.56N	15.819	139.4	2.8941	7.4674
	AKATSI	6.07N	15.612	53.6	3.1437	7.8947
COASTAL	ACCRA	05.36N	15.265	67.7	3.3803	7.7382
	TEMA	05.37N	15.515	14	3.3773	8.5205
	AXIM	4.52N	13.451	37.8	3.5919	8.3047
	SALTPOND	05.12N	13.233	43.9	3.2453	8.7653
	ADA-FOAH	05.47N	15.931	5.2	3.3799	7.5535
	TAKORADI	04.53N	13.814	4.6	3.5123	8.2345

Table 3 *Shows link budget design for the Northern zone*

Northern Zone	
Downlink EIRP from footprint (dBW)	52.5
Antenna Efficiency (%)	60
Frequency (GHz)	11.812
Antenna gain (dBi)	34.47
Slant range (km)	40132
Free Space Path Loss (dB)	205.96
Rain Attenuation (dB)	20.73
K (dBW/K/Hz)	-228.6
B_N (dBHz)	88.65
System noise temperature (K)	110
C/N (dB)	-20.19
Link Margin or Additional Power (dBW)	26.82
C/N (dB)	6.63
Required $\left(\frac{e_b}{n_o}\right)$ at MODEM (dB)	6.5
Recommended $\left(\frac{e_b}{n_o}\right)$ at MODEM (dB)	10.5

Table 4 *Shows link budget design for the Middle zone*

Middle Zone	
Downlink EIRP from footprint (dBW)	52.5
Antenna Efficiency (%)	60
Frequency (GHz)	11.812
Antenna gain (dBi)	34.47
Slant range (km)	40229
Free Space Path Loss (dB)	205.98
Rain Attenuation	24.87
K (dBW/K/Hz)	-228.6
B_N (dBHz)	88.65
System noise temperature (K)	110
C/N (dB)	-24.3
Link Margin or Additional Power (dBW)	31.42

C/N (dB)	7.12
Required $\left(\frac{e_b}{n_o}\right)$ at MODEM	6.5
Recommended $\left(\frac{e_b}{n_o}\right)$ at MODEM	10.5

Table 5 *Shows link budget design for the Southern zone*

Southern Zone	
Downlink EIRP from footprint (dBW)	52.5
Antenna Efficiency (%)	60
Frequency (GHz)	11.812
Antenna gain (dBi)	34.47
Slant range	40005
Free Space Path Loss (dB)	205.93
Rain Attenuation	25.42
K (dBW/K/Hz)	-228.6
B_N (dBHz)	88.65
System noise temperature (K)	110
C/N (dB)	-24.85
Link Margin or Additional Power (dBW)	31.42
C/N (dB)	6.62
Required $\left(\frac{e_b}{n_o}\right)$ at MODEM	6.5
Recommended $\left(\frac{e_b}{n_o}\right)$ at MODEM	10.5

Table 6 *Shows link budget design for the Coastal zone*

Coastal Zone	
Downlink EIRP from footprint (dBW)	52.5
Antenna Efficiency (%)	60
Frequency (GHz)	11.812
Antenna gain (dBi)	34.47
Slant range (km)	40117
Free Space Path Loss (dB)	205.95
Rain Attenuation	27.98
K (dBW/K/Hz)	-228.6
B_N (dBHz)	88.65
System noise temperature (K)	110
C/N (dB)	-27.38
Link Margin or Additional Power (dBW)	33.92
C/N (dB)	6.54
Required $\left(\frac{e_b}{n_o}\right)$ at the MODEM	6.5
Recommended $\left(\frac{e_b}{n_o}\right)$ at the MODEM	10.5

Table 7 *Shows link budget design for Ghana*

Ghana	
Downlink EIRP from footprint (dBW)	52.5
Antenna Efficiency (%)	60
Frequency (GHz)	11.812
Antenna gain (dBi)	34.47
Slant range (km)	40121

Free Space Path Loss (dB)	205.95
Rain Attenuation	24.75
K (dBW/K/Hz)	-228.6
B_N (dBHz)	88.65
System noise temperature (K)	110
C/N (dB)	-24.15
Link Margin or Additional Power (dBW)	30.92
C/N (dB)	6.77
Required $\left(\frac{e_b}{n_o}\right)$ at the MODEM	6.5
Recommended $\left(\frac{e_b}{n_o}\right)$ at the MODEM	10.5

DISCUSSION

In general, lower attenuation values were obtained for the Northern zone with an average of 20.73 dB. There was a sharp increase in attenuation for the middle zone, with an average value of 24.87 dB, a difference of about 4 dB. There was not much difference in attenuation between the middle and southern zones. The average attenuation value for the south was 25.41 dB. The highest average attenuation of 27.98 dB was obtained in the coastal zone. This is probably due to the high rain rates in the region especially for Axim. The result of this study suggests some differences in the attenuation levels for different climatic zones. Receivers of satellite services in these locations will be imparted differently. Hence system designers must consider these differences because the uncertainty might lead to an over-cost, both in initial expenses and in periodic expenses (Emiliani et. Al.,2004; Ojo et al.,2009). Larger antennas and better amplifiers can be used for optimum link performance in such areas. One of the ways of mitigating the effect of rain on the signal is to increase the transmit power. It can be seen from table 3 for the Northern zone that all other things being equal, the C/N ratio at the receiver will be -20.19 which implies the power at the receiver will be insufficient to allow for the proper decoding of data at an acceptable Bit Error Rate (BER). Since the energy-to-noise ratio required by the Modulator/Demodulator (MODEM) is 6.5 dB. An additional power of 26.82 dBW at the satellite transmitter is required. For the middle zone, the link will also not close requiring an additional power of 31.42 dBW. This is a very significant increase when compared to the Northern zone. It is also interesting to note that the power requirement between the middle zones and southern zones is the same. However the coastal zones require an additional power of 33.92 dBW to meet the required energy-to-noise ratio at the MODEM. Overall, a national average power increase of 30.92 dBW is needed. Power is however very expensive, the slightest increase could have cost implications on the consumer. This power requirement is too high and cannot be met practically.

CONCLUSION

It is important to quantify the amount of power to be received by consumers at different climatic zones in Ghana. A measure of the expected power, given the attenuation levels will inform system designers to determine the fade margin to add to the link budget. Hence if the total degradation is compensated by adding sufficient margin to the link budget, then the specified system performance objectives can be met. A lack of knowledge of the optimal power requirements can lead to power overestimation or underestimation. Overestimation will result in increased cost to the consumer whereas underestimation to lead to consumer dissatisfaction since the signal will be unavailable for most part of the time. Therefore as Ghana joins the rest of the world in migrating from analogue to digital television broadcasting these results can serve as a tool for system designers. There is the need to also explore other ways to optimize the use of existing power resources in combating rain fade other than just increasing the transmit power.

APPENDIX A

The step-by-step procedure for calculating the attenuation distribution is given below:

Step 1: Freezing height during rain H_r (km) is calculated from the absolute value of station latitude φ (degrees), preferably using the location under study

Step 2: The slant path length , L_s, below the freezing rain height is obtained:

$$L_S(\theta) = \begin{cases} \frac{(h_R - h_S)}{\sin\theta} & for\ \theta \geq 5^o \\ \frac{2(h_R - h_S)}{\left[sin^2\theta + \frac{2(h_r - h_S)}{R_e}\right]^{1/2} + \sin\theta} & for\ \theta < 5^o \end{cases}$$

(km) (A1)

where h_R = the rain height (km), from Step 1; h_S = the altitude of the ground receiver site from sea level (km); θ = the elevation angle; and R_E = 8500 km (effective earth radius). L_S can result in negative values when the rain height is smaller than the altitude of the ground receiver site. If a negative value occurs, L_S is set to zero.

Step 3: The horizontal projection is calculated as

$$L_G = L_S \cos\theta \quad \text{(A2)}$$

where L_S and L_G are in km.

Step 4: The rain intensity, $R_{0.01}$ (mm/h), exceeded for 0.01% of an average year is then obtained from the 1-minute integration rain-rate data and is used for calculating the specific attenuation, $\gamma_{0.01}$(dB/km):

$$\gamma_R = k\, R_{0.01}{}^{\propto} \quad \text{(A3)}$$

The parameter k and ∝ depend on frequency, raindrop size distribution, rain temperature and polarization. These can be obtained from ITU-R P. 838-5,2005.

Step 5: The horizontal path adjustment factor, $r_{0.01}$, 0.01% of the time is also given as :

$$r_{0.01} = \frac{1}{1+0.78\sqrt{\frac{L_G\,\gamma_R}{f}}-0.38\left(1-e^{-2L_G}\right)} \qquad \text{(A4)}$$

Step 6: Calculate the vertical adjustment factor, $v_{0.01}$, for 0.01% of the time

$$v_{0.01} = \frac{1}{1+\sqrt{\sin\theta}\left[31\left(1-e^{-\left(\theta/_{1+x}\right)}\right)\frac{\sqrt{L_R\gamma_R}}{f^2}-0.45\right]} \qquad \text{(A5)}$$

where

$$L_R = \begin{cases} \frac{L_G r_{0.01}}{\cos\theta} & km \ \ for\ \zeta > \theta \\ \frac{(h_R-h_S)}{\sin\theta} & km \ \ for\ \zeta \leq \theta \end{cases} \qquad \text{(A6)}$$

and

$$\zeta = \tan^{-1}\left(\frac{h_R-h_S}{L_G r_{0.01}}\right)\ deg \qquad \text{(A7)}$$

$$\begin{aligned} x &= 36 - |\varphi|\ \text{deg} && for\ |\varphi| < 36 \\ &= 0 && for\ |\varphi| \geq 36 \end{aligned} \qquad \text{(A8)}$$

Step 7: Determine the effective path length, L_E (km), is given by:

$$L_E = L_R\, v_{0.01} \quad \text{km} \qquad \text{(A9)}$$

Step 8: The predicted attenuation exceeded for 0.01% of an average year may then be obtained from:

$$A_{0.01} = \gamma_R \quad L_E \quad \text{dB} \qquad \text{(A10)}$$

Step 9: The attenuation A_p, exceeded for the other percentages, p, of an average year, in the range 0.001-5%, can be determined from

$$A_P = A_{0.01}\left(\frac{P}{0.01}\right)^{-[0.655+0.033\ ln(p)-\ 0.045\ \ln(A_{0.01})-\ \beta(1-p)\ \sin\theta]} \quad \text{dB} \qquad \text{(A11)}$$

where

$$\beta = \begin{cases} 0 & if\ p \geq 1\%\ or\ \ |\varphi|\ \geq\ 36^o \\ -0.005(|\varphi|-36) & if\ p < 1\%\ and\ \ |\varphi| <\ 36^o\ and\ \theta\ \geq\ 25^o \\ -0.005(|\varphi|-36)+\ 1.8-4.25\ \sin\theta & otherwise \end{cases} \qquad \text{(A12)}$$

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