RAINFALL ESTIMATION FROM SIGNAL ATTENUATION OF CELLULAR PHONE NETWORK(MICROWAVE LINK)

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ABSTRACT

This research gives a simple description of the employed rainfall retrieval algorithm from signal attenuation of a microwave link. Electromagnetic waves propagation and physics are used in this study to establish a simple R-k power law. Moreover an outlook of a complete and complex algorithm will be discussed in brief for future and further research.

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1: <u>INTRODUCTION</u>

Accurate rainfall measurements with high spatial and temporal resolutions are needed for water resource management, hydrological applications, agriculture, weather forecasting, climate research, validation of satellite based precipitation and many more applications. There is a shortage of this accurate rainfall data because of declining number of weather recording instruments including rain gauges worldwide (New et-al, 2001). In Botswana there are places where there are no rain gauges at all or no trained personnel to take daily measurements for rainfall, this has resulted in gaps on rainfall database and may hinder rainfall and rainfall related researches and projects or give inaccurate findings. This was the motivation for this research project, to find and establish alternative and complementary sources of rainfall information. Mobile communications infrastructures are all over the country. They use micro-waves or radio waves to transmit information from one location to another. The fact that the propagation of radio waves in the atmosphere can be hampered by rain along the signal propagation path has been known for a long time. Overeem, et-al. (2016) agrees that since 2006 various studies have shown that microwave links from operational cellular communication networks may be used for rainfall monitoring for various networks and climates, however the ability to observe other types of precipitation such as snow is limited. According to Hossain (2014), a research carried out at Bangladesh on rain attenuation prediction models, the rain attenuation of terrestrial microwave link depends on the amount of rain along with the size of the rain drops which intersects the links. Rain drops amounts and size vary temporaly and spatially therefore measuring the two parameters is not sufficient to predict the attenuation for the whole link path. He further outlined that there are several rain attenuation prediction models e.g. ITU model, Moupfouma model, Lin model and Sailva mello model. All of these models follow similar steps but for this research project a simplified power – law R-K relation will be used to develop the rainfall estimation algorithm. The telecommunications engineers have studied the physical relation between radio wave attenuation and rainfall intensity since the 1960s (leijnse, et-al. 2007). The employed rainfall retrieval method is based on measurements of the received signal level, estimation of the rain-induced attenuation, and the application of a power law relation between attenuation and rain rate to estimate path-averaged rain rate. According to Berne and Uijlenhoet (2007) during rainy periods, the microwave link signal is attenuated by the raindrops along its path. Microwave links take advantage of the fact that over a certain range of frequencies, the specific attenuation k [dB km^{-1}] is almost linearly related to the rainfall intensity R [mm h^{-1}]. Consequently, the path-averaged rainfall intensity, *R*, is nearly proportional to the path-averaged specific attenuation, *k*. The path-averaged specific attenuation itself is proportional to the path-integrated attenuation (PIA) which is measured by the link. In this way, it is possible to estimate the path-averaged rain rate. As the propagation of the link signal depends on the scattering from every individual raindrop along its path, the proportionality factor between, *R*, and ,*k*, depend on the frequency and the path length of the link as well as on the rain drop size distribution (DSD), which is a statistical means to describe the population of raindrops. Berne and Uijlenhoet (2007) also argues that due to the variety of microphysical processes involved in the formation and evolution of raindrops, the DSD is highly variable in space and time, Therefore it is important to investigate the influence of the variability of the DSD along the path on the rain-rate estimates using microwave links. This variability will depend on the type of rainfall and the climatic setting. The aims of this research project are to study the theory of how rainfall measurements can be obtained from attenuation of radio signal in a microwave link and to develop an algorithm (mathematical equations) that calculates the amount of rainfall from attenuation of signal strength on a microwave link. The second chapter of this project is the literature review which includes all the theories involved microwave links, electromagnetic waves propagation and how they are attenuated by hydrometeors. The third chapter entails the methodology, which deals with the algorithm development. The fourth chapter of this project includes the future work, this section gives an overview of how this project can be expanded in the future, it includes all the necessary variables required. Lastly is the discussion and conclusion chapter which gives a brief summary of this research project.

2: <u>LITERATURE REVIEW: THEORY</u>

A microwave link is a communication system that uses a beam of radio waves in the microwave frequency range to transmit information between two locations on earth. A link is a radio connection from one telephone tower to another whereas a link path is the path between two telephone towers. A link measures over two directions over the same link path, in which case there are two links but only one link path (Overeem et-al, 2016). Electromagnetic waves are used in a microwave link. According to Carr (1996) these are waves which travel through the vacuum of outer space, they do not need any medium in order to transport their energy from one location to another. They are created by vibration of an electric charge. These vibrations create a wave which has both an electric and magnetic component. The specific electromagnetic waves used in a microwave link are microwaves or radio wave – a form of electromagnetic radiation with wavelength ranging from one meter to millimeter with frequencies between 300 MHz (100cm) and 300GHz (0.1cm).

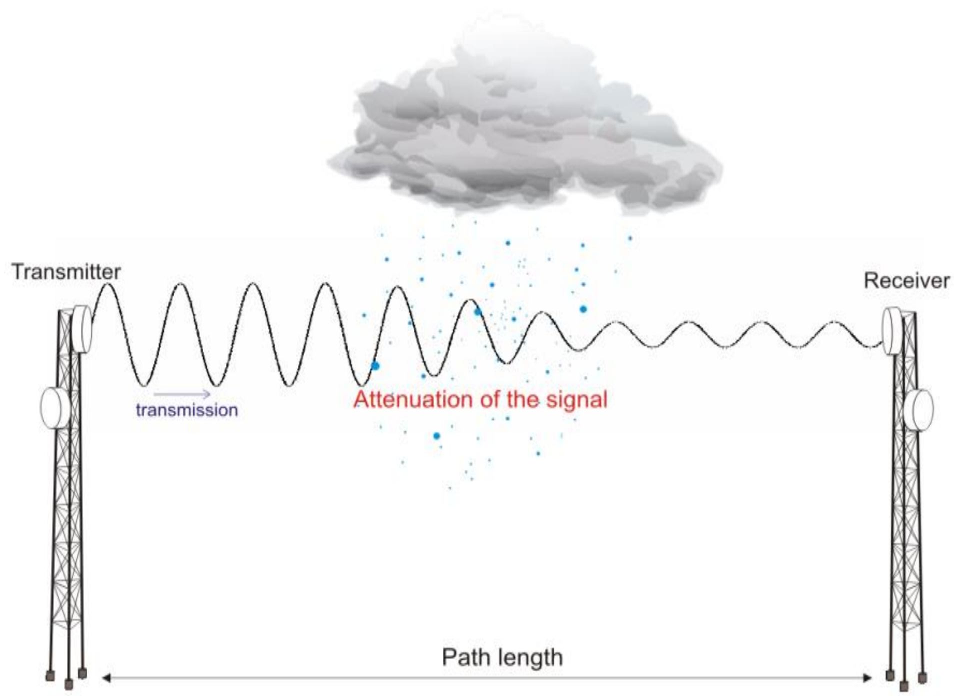

Figure 1: Shows a schematic microwave link and attenuation of the signal.

A simple one way microwave link includes; a transmitter, a receiver and antennas as shown in figure 1 above. The transmitter produces a microwave signal that carries the information to be communicated, it generates microwave energy at the required frequency and power level and also modifies it with the input signal so that it conveys meaningful information. At the transmitting end, the antenna emits the microwave signal from the transmission line into the free space. The antennas tightly focus the transmitted energy and receive energy mainly from one specific direction. These microwaves are affected by the phenomena of reflection, refraction, diffraction, absorption, polarization, and scattering as they are propagated through the atmosphere. During precipitation, the microwave energy can be absorbed or scattered in all directions from a passing wave (as shown in figure 2 below) hence causing a reduction in the strength of the signal (Kerr 1951). Overeem et-al. (2016) states that the cellular phone communications companies monitors the quality of their networks by operationally storing the receiving power at one end of the microwave link as a function of time. The rain induced path-integrated attenuation can be calculated from the decrease in received signal level with respect to the reference signal level (representative of dry weather) and converted to an average rainfall intensity over the link path.

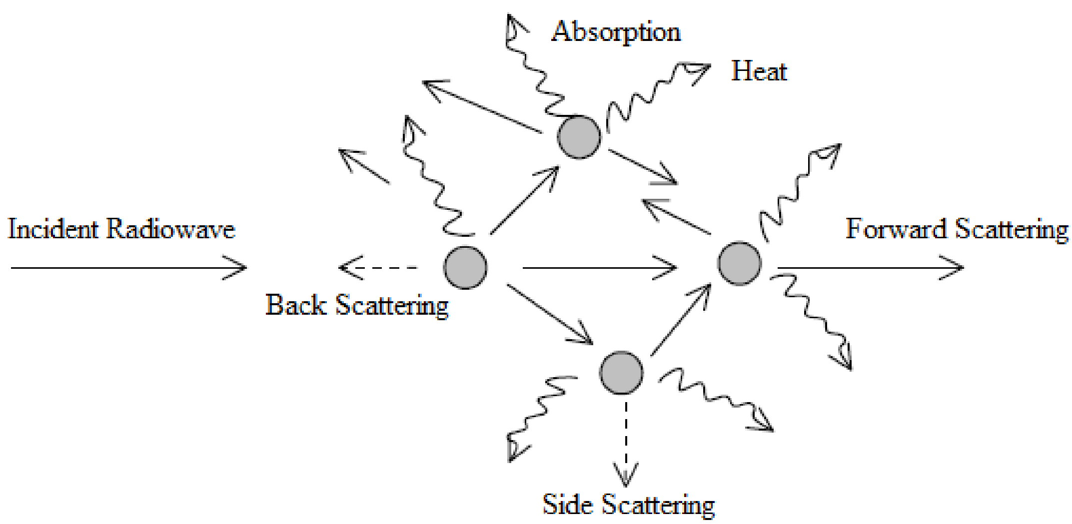

Figure 2: shows Interaction of an incident radio wave with rain drops.

Before planning a wireless network for cellular phone communications, it is necessary to determine the path loss and broadcast signal coverage for the location. Kestwal et-at. (2014) outlined that the microwave propagation is affected by changes in the lower atmosphere, the presence of hydrometeors such as rain, fog and water vapour in the radio wave path can produce an extremely significant effect in energy absorption. Rayleigh and Mie scattering are the main cause of attenuation at higher altitude of the atmosphere. Mello and Pontes (2012) states that the rain drops behave as dissipative media to the incident wave. The scattering is associated with modifications of wave propagation directions to satisfy the boundary conditions at the raindrop surfaces. The combination of these two effects causes attenuation, which depends on the drops conductivity and shape. Kestwal et-at. (2014) further states that as the precipitation rates increases, attenuation in radio communication is also increased, which shows adverse effect at microwave and millimetric frequencies, since electromagnetic waves are most affected by scattering and absorption phenomena. With respect to these hydrometeors, the path loss due to rain attenuation has been recognized as major obstacles in design of microwave communication link operating at frequencies above 10 GHz. According to Kestwal et-al. (2015) the specific rain attenuation, α depends on the forward scattered electromagnetic wave (and its effects are influenced by the water temperature, the refractive index of water and radio link frequency) from which the extinction cross-section is calculated. When an electromagnetic wave passes through a medium containing raindrops, part of its energy is absorbed by the raindrops and dissipated as heat, and the remainder is scattered in all directions (figure 2). This scattered part introduces unwanted or interfering signals into the communication receiver that may mask the desired signal, thereby causing reduction of signal strength or power (attenuation). Overeem, et-al. (2016) have also conducted a similar study which shows that in general, power losses along links are measured and stored by cellular communication companies to monitor the stability of their link networks. At the used radio frequencies these losses are apart from free space losses, mainly the result of attenuation by rainfall. Raindrops absorb part of the incident wave and, in addition, scatter some of the energy out of the beam. The resulting attenuation becomes larger for increasing numbers and sizes of the raindrops present along the beam.

3: METHODOLOGY: ALGORITHM DEVELOPMENT

Rainfall Estimation Using Single-Frequency Microwave Links

In the frequency range of microwave links (from about 5 to 50 GHz), electromagnetic waves interact with raindrops when propagating through rainfall, because their wavelengths are of the order of magnitude of the raindrop sizes. The drop size distribution is given by $N_D = N_0 e^{-AD}$ where D is the drop diameter and N_0 is the value for N at a diameter of zero. The DSD is used to obtain the specific attenuation and rainfall rates (Marshall and Palmer, 1948). According to Berne and Uijlenhoet (2007) the (one-way) specific attenuation k [dB km^{-1}] affecting the link signal (at a wavelength λ) can be expressed as a function of the DSD given by:

$$k = \frac{1}{\ln 10} \int_0^{\infty} \sigma_E(\lambda, \mathrm{D}) N(D) dD \quad (1)$$

Where D denotes the equivolumetric spherical drop diameter [mm] and σ_E(D) denotes the extinction cross-section [cm^2] due to a drop of diameter D, and N denotes the DSD: *N*(D)*d*D [m^{-3}] is the number of drops, in the diameter interval [D, D + *d*D], per unit volume.

Similarly, the rainfall intensity *R* [mm h^{-1}] can be expressed as a function of the DSD, given by

$$R = 6\pi 10^{-4} \int_0^{\infty} D^3 v(D) N(D) dD \quad (2)$$

Where *v*(D) [m s^{-1}] denotes the terminal fall velocity of a raindrop of diameter D. It is worth noting that R does not depend on the wavelength of the link because it is a flux of water, totally independent of the interaction between microwaves and hydrometeors.

Because the integrands of (1) and (2) are similar at frequencies used for microwave links, *R* and *k* are almost linearly related (i.e they are directly proportional). Putting the constant of proportionality gives the *R*-*K* relation which is given by:

$$\mathrm{R} = \alpha \mathrm{k}^{\beta} \quad (3)$$

Where coefficient α and exponential β depends on the link frequency and the DSD. Generally β can be approximated to unity (1) because at frequency range of 15.3 – 45.5 GHz (which most microwave links operate at, around 30GHz) the rain drops are large enough to interact with the radio waves thus causing signal attenuation. Therefore, equation (3) simplifies to:

$$R = \alpha\ k \quad (4)$$

Where, k, [dB km^{-1}] denotes the one-way path-averaged specific attenuation, which can be derived from microwave link measurements. Knowing the value of α, it is possible to estimate the path-averaged rain rate, R, using a single-frequency microwave link. However, the linearity of the R-k relation and the uncertainty associated with its coefficients depend on the frequency of the link as well as on the variability of the DSD along the link.

4: FUTURE WORK

This research study opens several new avenues of future study to better understand the rainfall retrieval capability of commercial microwave links. Further work could be dedicated to assessing the long-term effects of the cellular network used for rainfall monitoring based on a more extensive dataset, complex mathematical equations and less physical assumptions.

There are several steps to be followed in this rainfall retrieval algorithm as discussed by Overeem, et-al. (2016). The first step is preprocessing of link data, secondly; wet–dry classification. Third step is to reference signal determination then fourthly removal of outliers due to malfunctioning links. The fifth step is to correct received signal powers, then lastly computation of mean path-averaged rainfall intensities.

1. Processing link data: To compute path-averaged rainfall intensities, maximum and minimum received powers of a time interval are required for a given length. The following variables are needed for each link and time interval: microwave frequency f (GHz), minimum and maximum received power P_{min} and P_{max} (dBm), path lenth L (km).
2. Wet – dry classification: In order to define wet and dry periods, it is assumed that rain is correlated in space and hence that several links in a given area should experience a joint decrease in received signal level in the case of rain. A time interval is labelled as wet if at least half of the links in the vicinity (default radius is 15 km, but this can be modified to better match other time intervals) of the selected link experience such a decrease.
3. Determination of reference signal level: The performed classification of rainy and non-rainy time intervals serves two purposes: (1) it allows for determining an accurate reference signal level or base level, which needs to be representative of dry weather; (2) it prevents non-zero rainfall estimates during dry weather. The reference signal level Pref is computed for each link and time interval separately from the minimum and maximum received signal powers (dBm), Pmin and Pmax respectively. If no wet–dry classification has been applied, the reference level is determined over all time intervals in the previous 24 h.
4. Filter to remove outliers: Malfunctioning links can cause outliers in rainfall retrievals. These outliers can be removed by using a filter that is based on the assumption that rainfall is correlated in space. The filter discards a time interval of a link for which the

cumulative difference between its specific attenuation and that of the surrounding links (i.e. within a default radius of 15 km) over the previous 24 h becomes lower than the outlier filter threshold. This criterion is applied to specific attenuation derived from uncorrected minimum received power. Running the outlier filter is optional.

5. Correction of received powers: Subsequently, corrected minimum (P_{Cmin}) and maximum (P_{Cmax}) received powers are computed for each time interval. In case of no wet–dry classification the time interval of P_{min} is always considered wet.
6. Computation of path-averaged rainfall intensities: lastly the path-averaged rainfall intensities are computed from the corrected minimum and maximum received signal powers.

These steps involve a lot of complex equations and very few assumptions, so future studies can be carried out involving them. There are many variables involved, given in table 1 below. In a study carried out by Overeem, et-al. (2012), it have been shown that for the used cellular network, the loss of power is inferred from the decrease in received power only, the transmit powers being nearly constant (±0.2 dB). The received signal powers have to be corrected before accurate path-averaged rainfall intensities can be obtained. Although signal losses not related to rainfall are often smaller than those during rain, they frequently occur and could result in an overestimation of rainfall intensity when not properly accounted for, therefore unwanted signal fluctuations has to be removed. In addition, a filter is applied to exclude a link when its received power deviates too much from that of the surrounding links.

According to Overeem, et-al. (2016) reflection of the beam or dew formation on the antennas can result in non-zero rainfall estimates thus occasionally decreasing the received power during non-rainy periods. To prevent rainfall overestimation a classification of wet and dry periods is needed, some can be applied to the received powers or signal attenuation when they are sampled at very high frequencies. Attenuation due to wet antennas give rise to overestimation of rainfall and needs to be compensated. In order to complete path-averaged rainfall intensities, received signal powers should be obtained from the mobile communications company microwave links.

Table 1: Most important variables used in the functions and/or sub-functions of the rainfall retrieval algorithm.

Name of Function	Symbol	Unit	Description
a	a	Mm h^{-1} dB^{-b} km^{b}	Coefficient of R–k power law
A max	A_{max}	dB	Maximum rain-induced attenuation
A min	A_{min}	dB	Minimum rain-induced attenuation
b	b	-	Exponent of R–k power law
F	F	dB km^{-1} h	Computed for filter to remove outliers
Frequency	f	GHz	Microwave frequency
PathLength	L	km	Path length
Rmean	$<R>$	mm h^{-1}	Path-averaged rainfall intensity
Pmin	P_{min}	dB	Minimum received power
PminCor	P_{Cmin}	dB	Corrected minimum received power
Pmax	P_{max}	dB	Maximum received power
PminCor	P_{Cmax}	dB	Corrected maximum received power
Pref	P_{ref}	dB	Reference level

5: CONCLUSION

The main objective of this research project was to relate signal attenuation of microwave link due to rainfall to the amount of rainfall and formulate an algorithm that estimates rainfall amounts. This study has shown that by employing physics, electromagnetic wave propagation and a simple power law relation, signal attenuation due to rainfall could be used to obtain rainfall intensity. Microwave links such as those employed in cellular communication can potentially be used for the estimation of rainfall. Rain attenuation is caused as a result of absorption of part or all of the signal's radiation power by the raindrop. The study further explores the possibilities for a more complex retrieval algorithm.

APPENDIX

Taylor Series Expansion of Point Scale R-k Relation

This appendix shows that the R-k relation at the point scale $R(k) = \alpha k^{\beta}$ provides a good approximation for the path-averaged rainfall intensity *R* as well. A second order Taylor series expansion of R(k) is developed around *k* to obtain a better approximation to the relationship between *R* and *K*. (Overeem *et-al*, 2011).

$$R(k) = R((K)) + \big(K - (k)\big)R'\big((K)\big) + \frac{1}{2}\big(K - (K)\big)^2 R''\big((K)\big) + \cdots \qquad \text{(A1)}$$

Where $R'\big((K)\big)$ is the first order and $R''\big((K)\big)$ is the second order derivative of $R(k)$ with respect to K, evaluated at $= (k)$. Equation (A1) can be approximated by:

$$R(k) \approx \alpha(k)^{\beta} + \big(k - (k)\big)\alpha\beta(k)^{\beta-1} + \frac{1}{2}(k - (k)^2\alpha\beta(\beta - 1)(k)^{b-2} \qquad \text{(A2)}$$

Taking averages (expectations) on both sides gives:

$$(R) \approx \alpha(k)^{\beta} + \frac{1}{2}var(k)\alpha\beta(\beta - 1)(k)^{b-2} = \left[1 + \frac{1}{2}\beta(\beta - 1)\frac{var(k)}{(k)^2}\right]\alpha(k)^{\beta} \qquad \text{(A3)}$$

where $k = (k)$ is the variance of *k* along the link. This can be written as:

$$(R) \approx \left[1 + \frac{1}{2}\beta(\beta - 1)CV_k^2\right]\alpha(k)^{\beta} \qquad \text{(A4)}$$

This equation shows that the path-averaged rainfall intensity also depends on CV_k, the coefficient of variation (ratio of standard deviation and mean) of the specific attenuation along the link. The spatial variability of *k*, and hence that of rainfall, is of influence. Particularly in convective rainfall, CV_k can be considerable. Because the spatial variation of *R* cannot be derived from the received power, CV_k cannot be calculated.

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