Clear Air and Precipitation Millimeter-Wave Point-to-Point Wireless Link Prediction Based on Terrain Path Profile in Semi-Arid Climate

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Abstract*— This paper presents a 38-GHz point-to-point wireless link prediction study using terrain path profile and aims to be used for the foreseen radio communication planning and design in a new metropolitan constructed area in Riyadh, Saudi Arabia, which is a semi-arid region. Point-to-point link simulations were made using both of Longley-Rice and ITU-R P.530 models to help designing reliable wireless broadband solutions so that wireless broadband service providers can consistently fulfill or exceed performance expectations. As the assumed link is in a semi-arid climate, it is characterized by low precipitation rates. However, these rates can cause downtime on the radio link due to using millimeter-waves which experience high fading. For the link availability study and analysis, many technical parameters are considered including different field measured rain rates, a various transmitter (Tx) antenna heights, elevation and land cover data (terrain profiles between the Tx and the receiver (Rx)), antenna coverage, etc. The results showed that the fade margin tends to be smaller at lower antenna height due to the absence of the clear line of sight (LOS), and at high precipitation rates caused by the high attenuation in millimeter-waves. Additionally, it has been found that the link will be unavailable when the rain rate of $R_{0.01}$ or more is exceeded. Furthermore, it has been shown that the highest link availability percentage for the positive fade margin is 99.997% and 99.993% in clear air and the precipitation rate of $R_{0.25}$ conditions, respectively.

***Index Terms*—Antenna Height; Fade Margin; Link Availability; Precipitation; Propagation Prediction.**

I. INTRODUCTION

Microwave radio communication terrestrial links, ranging from 1-300 GHz, usually provide large bandwidth and high capacity for contemporary applications. The millimeter-wave frequency bands, as a part of microwave spectrum including Ka-band, as a key candidate frequency spectrum for the 5G to support these applications using telecommunication technologies including mobile, fixed, and satellite that is intended to be integrated. The Ka-band millimeter-waves, including 38 GHz, are characterized by fading due to ground reflections of up to 8 dB and atmospheric fading of 20-40 dB [1]. In addition, when moving to smaller millimeter-waves, the feasible transmission distance becomes shorter (in order of hundreds of meters instead of kilometers) due to a lot of losses that face the signal particularly when there is no line-of-site (LOS) between the transmitter (Tx) and receiver (Rx). Moreover, millimeter-wave signals are naturally not capable to easily penetrate walls or material, and the hardware components operating at these wavelengths, such as analog-to-digital converters (ADC), might also not be cost effective [2]. Furthermore, the previous studies such as [3] showed that higher frequencies tend to be influenced by rain fading rather than multipath which is a phenomenon accompany to lower frequencies. In addition, the rain fading at the higher frequencies becomes more critical especially in areas with the tropical weather [3].

Studies performed in Saudi Arabia [4] [5] stated that, on average, around 50% and 20-30% of all rain befalls at intensities in excess of 20 mm/hr and 40 mm/hr, respectively. However, the statistical analysis of rainfall collected data from stations specifies that precipitation is variable in space and time. Specifically, the reality and past field studies demonstrate that Riyadh is a semi-arid region [6] and flat topography where variations of precipitation are not so large. The average monthly rainfall amount at Riyadh for data collected during the period of 1970-2003 [6] shows that Riyadh area exhibits temporal variability of rainfall. That is, the maximum amount of rainfall received in Riyadh occurs in March and April, while the period between June-October is the dry period.

For the purpose of designing reliable wireless broadband point-to-point solutions, real rainfall field measurements are necessary to meet expected performance and simulate the wireless point-to-point link as a fixed broadband terrestrial solution in all propagation conditions. In this context, Longley-Rice or Irregular Terrain Model (ITM) model is considered the common broadly known overall purpose path loss model to evaluate terrestrial links. Generally, there are three widespread radio propagation standards used for creating radio environment maps; the Longley-Rice ITM point-to-point, Okumura-Hata with diffraction and International Telecommunications Union-Radio communications (ITU-R) P.1546 propagation models [7] [8]. In spite of the accuracy of the models can be about 2 to 3 dB and standard deviation of 5 to 6 dB, if we exclude multipath effect, the ITM model is the best choice in case of terrain data profile is available [9]. It is worth to mention that ITM model is much like ITU-R P.452 model but ITU-R 452 includes some local clutter losses computations based on land cover classification data, otherwise both models can be supposed to be quite analogous [10]. Although, the above-mentioned terrain profile-based models do not include precipitation effect into account. Therefore, there is a high necessity to add the precipitation effect to the total path loss using a suitable model, such as ITU-R P.530 [11].

The presented paper predicts a point-to-point wireless link status based on (1) irregular terrain path profile in Riyadh city using Radio Link Longley-Rice simulation model to get the link availability during clear air condition particularly in dry months (May-October) and (2) ITU-R P.530-16 model to compute the fading caused by precipitation during the rainfall period (November-April) and adding the effect to the ITM model. This prediction study tries to support the foreseen measurements in the modern King Abdullah Financial District (KAFD) area, which is currently under construction, in order to be connected with surrounding facilities and vital entities. Longley-Rice model has been adopted as a standard by the Federal Communications Commission (FCC) and it is an empirical model used to predict atmospheric attenuation which realistically is extremely difficult to mathematically expressed [12]. It covers wide spectrum frequency bands in the range 20MHz-40GHz and for path lengths of about 1-2000 km [13], and it can be utilized in wide variety of terrain profiles. This model takes into account the path geometry of terrain and the refractivity of the troposphere to calculate transmission path loss and uses geometrical sight in conjunction with the two-ray model in order to evaluate the power signal strength at the receiver. Therefore, Longley-rice model consists of most of the relevant propagation models which include diffraction over multiple knife edges, rounded edge and over irregular terrain; atmospheric attenuation and atmospheric stratification; tropospheric propagation models; polarization effects; specific terrain data, various climatic areas, etc. [12], [14].

The rest of this paper is organized as follows. In section II the simulation scenario including the path and link parameters, and measured rain rates in Riyadh region are described in details. Simulation results, analysis and discussions are presented in section III. Finally, we conclude the paper in section IV.

II. Path, Link, and Precipitation Description

In this section, the path parameters, link parameters and measured rain rates in Riyadh region are described.

A. Path Parameters

The planned point-to-point path link scenario is assumed to be in Riyadh metropolitan area. The first point is situated at latitude and longitude of 24.764135°N and 46.641083°E, respectively, which is location of the KAFD to be as a transmitter base station (BS), whereas Al-Imam Mohammad Ibn Saud Islamic University (IMSIU) Tower is adjusted as a receiver point at 24.805970°N and 46.699609°E. Thus, the KAFD-IMSIU Tower path length hop is 7.52 km.

The Path profile along the link is illustrated in Figure 1 using Radio Link tool [15]. The terrain profile for the path determines the ground elevation by 632.1 m and 663.6 m above sea level (a.s.l) for KAFD and IMSIU sites, correspondingly. For the path clearances, the Fresnel zone radius, r, is obtained to be 3.86 m, and 80% of Fresnel zone radius is 3.09 m. For a good link, clear line of sight (LOS) is required to maintain enough strength of the signal. Normally, a percentage of blockage of 20% Fresnel zone can cause slight loss to the link. But, further than 40% blockage, signal loss will be serious. The formula used for determining the radius of the widest point of the Fresnel zone (m) is:

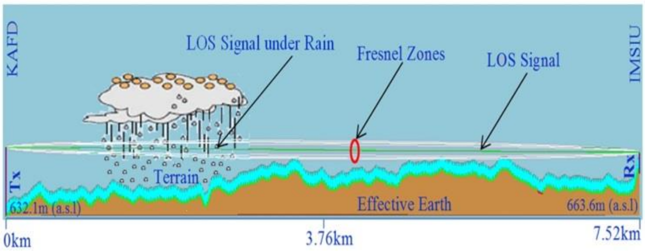

Figure 1: The terrain path profile and precipitation scenario of KAFD-IMSIU link

$$r = 8.657 \times \left(\frac{d}{f} \right)^{0.5} \tag{1}$$

where d is the distance, km, between the transmitter and receiver antennas, and f is the carrier frequency, GHz.

B. Link Parameters

The main link budget estimated by the ITM model takes into consideration all significant losses except multipath and building losses. The total losses in addition to free space loss include urban loss, obstruction loss and statistical losses. Table 1 lists the main parameters of the 38GHz KAFD-IMSIU link which are inputs to ITM model. In this table, it is indicated that the KAFD transmitter uses a directional antenna with a gain of 17 dB and radiates a power of 20 watts (43.01 dBm), while the receiver sector antenna at IMSIU has a gain of 2 dB, and the receiver has a threshold of -113.02 dBm (0.5 μV). Also, it is assumed that the path length link (7.52 km) is with a required link reliability of 70%. In addition, the azimuth angles for the Tx and Rx antennas have been adjusted at 70° and 225° for KAFD and IMSIU antennas, respectively.

Table 1
The KAFD-IMSIU Link Parameters (with no precipitation rates)

Description		Value
radio operation frequency		38 GHz
Path distance		7.52 km
transmitter		
	power transmitted	43.01 dBm
	latitude	24.764135°
	longitude	46.641083°
	ground elevation (a.s.l)	632.1 m
	antenna gain	17 dBi
	antenna height	15-70m
	antenna azimuth	70°
	antenna type	directional antenna
	line loss	3.0 dB
receiver		
	latitude	24.805970°
	longitude	46.699609°
	ground elevation (a.s.l)	663.6 m
	antenna height	15 m
	antenna azimuth	225°
	antenna type	sector antenna
	antenna gain	2 dBi
	sensitivity	-113.02 dBm (0.5 μV)
	line loss	0.5 dB
polarization		horizontal
reliability		70%
surface refractivity		-400 N-units
average terrain (hills)		Δh=90 m
Riyadh climate (continental)		301 N-units

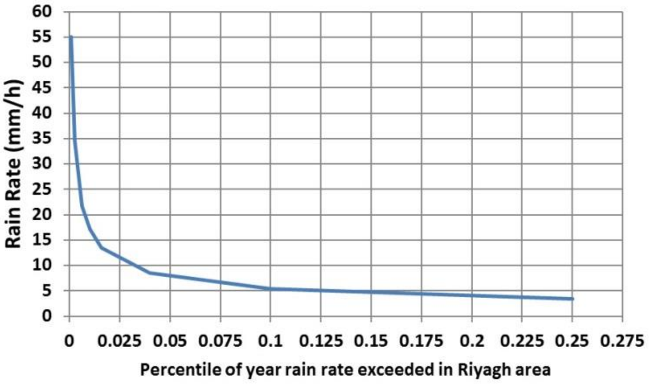

Figure 2: The measured rain rate in Riyadh at different percentages of rain rate exceeded

C. Precipitation Conditions in Riyadh

In Figure 2, the precipitation rate distribution for different percentages of precipitation rate exceeded is shown. This data has been extracted based on 18-year rainfall data collected during the period of 1963-1980 [16]. The collected weather-data is converted from rainfall intensity in millimeter (mm) into precipitation rates in millimeter per hour (mm/hr) through the use of the following expression:

$$R = PI \times \frac{60}{T} \quad (2)$$

where R is the precipitation rate (in mm/hr), and PI is the maximum precipitation intensity (in mm) during a time interval of T (in min). In Figure 2, it can note that the measured precipitation rate exceeded 0.01% of the time (52.56 minutes per year) is $R_{0.01}$=17.17 mm/hr and the maximum precipitation rate is 55.09 mm/hr for a time of 13.14 min/yr, i.e., a percentile of 0.0025%, whereas the measured minimum precipitation rate in Riyadh is 3.36 mm/hr and its cumulative time is 21.9 hr/yr.

III. Results and Discussion

A. The Received Power Strength

When the 38 GHz KAFD-IMSIU link has been created by adjusting a fixed height for the IMSIU antenna at 15 m and varying the KAFD antenna height from 15-70 m by 1 m step, the power signal strength, dBm, has obtained. The received signal power strength (RSP) for clear air and precipitation condition at an average rain rate of 30 mm/hr are plotted in Figure 3. The received RSP for precipitation conditions is computed through using ITU-R P.530-16 to get the excess path attenuation and the rain attenuation for the KAFD-IMSIU link, and then adding the attenuation to the received RSP in clear air condition. The specific path attenuation and the rain attenuation for KAFD-IMSIU link are computed for horizontal polarization. It was found out that the specific path attenuation and the rain attenuation for the average rain rate are 8.02 dB/km and 45.23 dB, respectively. It can be noted that the RSP fluctuates with transmitter antenna height and the link outage can occur when the antenna height is less than 21m in clear air condition. When the rain rates exceeded are taken into account, it is demonstrated that there is no link connection at all when the precipitation rate is 55.09, 34.64, 21.7 and 17.17 mm/hr. The apparent fluctuation in signal power strength with increasing Tx antenna height may be due to the fact that the radius of Fresnel zones is small. Vividly, at Tx antenna height less than 21 m clear air condition there is no clear LOS of KAFD-IMSIU link and the received signal strength becomes less than the receiver sensitivity, and then the receiver cannot capture the signal from the transmitter. After 21 m transmitter height, the ratio of Fresnel zone earth clearance to Fresnel zone radius starts to increase till it becomes more than 60%, where the radio path is said to be “Clear LOS” and no diffraction loss experiences. Additionally, the above-mentioned rain rates weaken the signal strength and because high attenuation makes the received signal lower than the receiver sensitivity. Even though, when the precipitation rate is 13.53, 8.51, 5.36, or 3.36 mm/hr the connection is possible for the link according to the technical parameters given in Table 1. In addition, the latter rain rates can allow for connection provided fulfill the transmitter antenna height mentioned in Table 2. For example, for precipitation rate of 8.51 mm/hr the transmitter antenna height should be 23 m, but the height should be 25 and 36 for precipitation rates of 5.36 mm/hr and 3.36 mm/hr, respectively. Moreover, it can be seen that the maximum RSP is at Tx antenna height of 44 m for all cases and it equals -88.08, and -94.58 dBm for clear air and 0.016% precipitation exceedances, correspondingly.

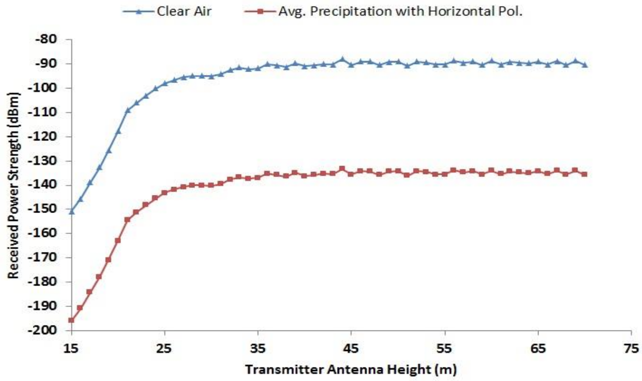

Figure 3: The received signal power strength versus transmitter antenna height in clear air and the average precipitation condition

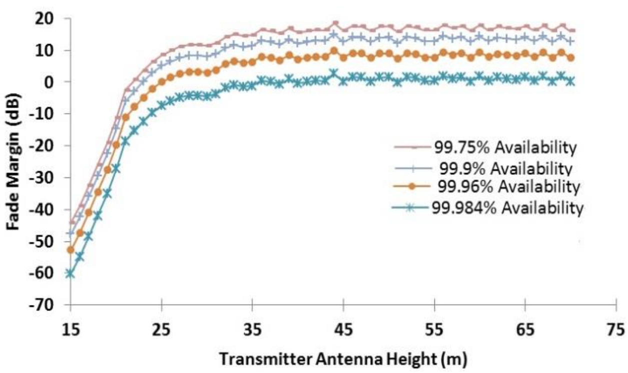

Figure 4: The fade margin versus transmitter antenna height in various precipitation condition

B. The Fade Margin

The fading margin of the received signal power strength for less poor propagation conditions is given in Figure 4 and the most important values are tabulated in Table 2. It is clarified that the clear air case has the maximum fade margin of 24.94 dB. While the fade margin value becomes positively less in precipitation conditions of 0.016, 0.04, 0.10 and 0.25% exceedance, it is negative for the other rain rate exceedances: 0.001, 0.0025, 0.0063 and 0.01%, in which there is no communication possibility due to fact that the received signal is lower than the receiver sensitivity.

Table 2
Acceptable RSP, Maximum RSP and Fade Margin (NA: not applicable)

Propagation Status/ Precipitation Exceedance	Min. Acceptable RSP (dBm)	Min. Tx Height (m)	Max. RSP (dBm)	Max. Fade Margin (dB)
0.0% (clear air)	-109.18	21	-88.08	24.94
0.001%			-113.18	-0.16
0.0025%	NA	NA	-122.08	-9.06
0.0063%			-139.46	-26.44
0.01%			-165.38	-52.36
0.016%	-112.44	22	-94.58	18.44
0.04%	-112.87	23	-97.98	15.44
0.10%	-112.95	25	-100.34	12.68
0.25%	-112.48	36	-108.18	4.84

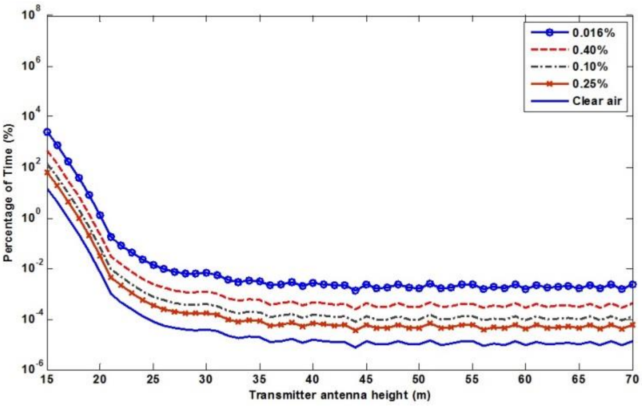

Figure 5: The percentage of time versus transmitter antenna height for the KAFD-IMSIU link in clear air and precipitation

C. Link Availability

The percentage of time, P_w, is used to predict the link availability for the various propagation conditions. For this purpose, the fade depth, *FM*, is utilized in the average worst case/month as an effective parameter in the Barnett-Vigants mathematical model to estimate the link availability. The Barnett-Vigants model is expressed as follows:

$$P_w = \left(\left(6 \times 10^{-7} C f d^3\right) 10^{-0.1\,FM}\right) \quad (3)$$

where *C* indicates to the geoclimatic factor, its value for good propagation conditions in dry climates, such as in Riyadh city, is 0.25, *f* denotes to the carrier frequency, GHz, *d* represents the point-to-point link distance, km, and *FM* is the fade margin, dB. The link availability versus transmitter antenna height is plotted in Figure 5.

From Figure 5, it can be noted that the high-level link availability is in clear air condition and it equals 99.999% at 44 m antenna height of the transmitter which can be considered an optimum height and it can be said that the link is reliable at this point and condition. On the other hand, the link availability is negative and unreliable at all with using lower antenna heights than 21 m. From the results, it has been found that the average link availability for the positive fade margin is approximately 99.997%.

For precipitation conditions, the link availability is null for rain rate intensity more than 17.17 mm/hr. Whereas, the link availability using the positive fade margin for the other precipitation rates is illustrated in Figure 5 as follows. The results indicate that the lowest precipitation rates make the link availability higher than the more intensity rates. For example, the precipitation rate of $R_{0.25}$ has the maximum link availability (99.993%) while the rate of $R_{0.016}$ makes the link availability minimum (99.801%) amongst the other rates in Figure 6. This is true due to the fact that more precipitation rate experiences more attenuation affects the signal and then low power strength level reaches the receiver which can not receive the lower power signal than its threshold. Moreover, as shown in Figure 6, the link availability can be maximum in clear air condition (at rain rate percentile of 0%) for both optimum transmitter antenna height and minimum positive fade margin. Additionally, the link availability can score 99.54% at 0.01% precipitation exceedance for the optimum transmitter antenna height, but at the minimum positive fade margin the availability of the link is absolutely unacceptable. However, the link availability at the optimum transmitter antenna height is maximum (99.997%) in precipitation condition at rain rate of 0.25%. Furthermore, at the minimum positive fade margin, the link availability has a maximum value of 99.55% at the same precipitation rate, but it is lower than standard values.

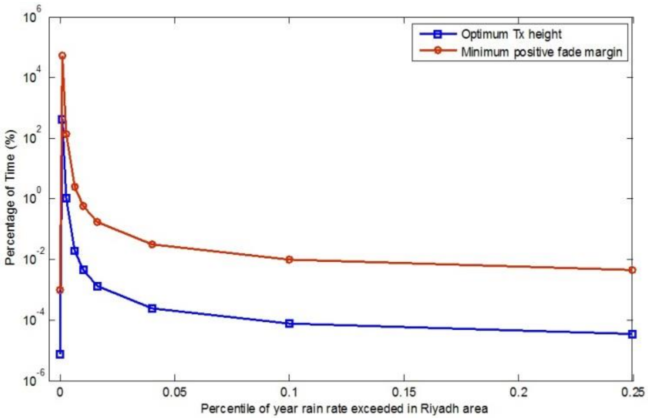

Figure 6: The percentage of time versus the percentage of year rain exceeded in Riyadh area

The small level of link availability due to precipitation attenuation seems not enough for link reliability and can be elevated by employing several techniques for such propagation conditions. These techniques include a backup link with low frequencies (for example, 5.8 GHz link) during precipitation time, automatic gain control (AGC) voltage, and an antenna with higher gain. When comparing the curves in Figure 6 with the common link availability target value, 99.99%, it can be realized that may be no need to use precipitation mitigation techniques during the propagation of $R_{0.25}$ to increase the link availability, whereas the higher rates of precipitation requisite utilizing mitigation techniques to ensure 99.99% or any other targeted values for link availability.

IV. CONCLUSION

This article presented a prediction study for KAFD-IMSIU point-to-point link in Riyadh city using Longley-Rice and ITU-R P.530 models. To the best of the author's knowledge, no study has been carried out using these two models together to manage propagation prediction studies in clear air and precipitation condition climates, simultaneously. The results demonstrate that the highest link availability percentage for the positive fade margin in clear air and for the optimum transmitter antenna height at $R_{0.25}$ is same, 99.997%. Additionally, the results revealed that precipitation rates have a significant negative effect on the link availability even when the precipitation was not so heavy due to the high attenuation at the millimeter-waves.

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