



Research Article

Performance of the DBS Satellite Receiver under the Impact of Rainfall and Terrestrial Interference

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This article presents a new study on the feasibility of operating a direct broadcasting satellite (DBS) system under the effect of both precipitation and interference from a fixed service (FS) at K-band in a semiarid region. The carrier-to-noise plus interference ratio (CNIR) as a protection criterion has been adopted to make sure that the receiver of the DBS system operates with an acceptable performance under rainfall and interference from FS. Various measured data for rainfall in different areas have been utilized to investigate different rain rate exceedance percentages. Results have been shown that areas with high rain rates have a small CNIR at the DBS receiver and require large protection distances compared to low-rain rate areas and vice versa. Some mitigation techniques have been suggested to alleviate the effect of rain and terrestrial interference on the DBS receiver performance.

1. Introduction

The overcrowding in lower spectrum frequency bands like C-band and Ku-band is predictable to lead new systems to move gradually more to K-band and, in a longer-term, to higher bands [1, 2] such as in the 5G and 6G generation systems. Thus, frequency bands higher than 6 GHz will be highly significant in future systems related to Earth-space connection. In those bands, attenuation due to rain represents a dominant factor that reduces the system availability and negatively affects its performance especially in heavy rain areas such as in south Saudi Arabia. Thus, the rain attenuation impacts higher frequency bands and it is more harmful than that in the lower bands [3, 4]. According to ITU-R, the 21.4–22 GHz band has been allocated to 3 dissimilar services: fixed, mobile, and satellite broadcasting services in the 1st and 3rd regions including Saudi Arabia which is considered as a semiarid area. Therefore, the cochannel interference is certain, which may affect the performance of the direct broadcasting satellite (DBS) system receiver. As a result, the

satellite communication system must be designed to be reliable against interference from terrestrial systems [5]. The interference can be estimated concerning the receiving system criteria of the carrier-to-noise plus interference ratio (CNIR) [6]. The Saudi Communications and Information Technology Commission (CITC) proposed to use the 21.4–22 GHz for both the DBS system and fixed service (FS) [7]; thus, this paper will consider the cochannel interference from FS to the DBS system as well as the rain attenuation effect with various rain rate exceedance to investigate the effect of these factors on the DBS system receiver performance and then to determine the feasibility of the concurrent operation of the DBS system receiver and FS service.

The paper is organized as follows. Relevant prior work and contribution are discussed in Section 2. Criteria of dissimilar system coordination are presented in Section 3. In Sections 4 and 5, the rain distribution, methodology, and proposed scenarios are explained in detail. The criterion of the CNIR and communication link simulation are provided in Section 6. Assumptions, results, and discussion of the

obtained results are recorded in Section 7. In Section 8, remarkable conclusions have been drawn.

2. Relevant Prior Work and Contribution

A number of publications reported the research in the field of concurrently operating the terrestrial fixed service (FS) with satellite services (SS) (broadcasting (BSS) and fixed (FSS)), in different spectrum frequency bands [4, 7–18]. Most researches mainly study the performance of satellite receiver affected by the FS system based on spectrum sharing policies between the dissimilar systems. These articles essentially focus on the impact of interference, rainfall, shared system parameters, and its impacts on sharing performance. The paper characteristics and the significant remarks are summarized in Table 1. In addition, for the purpose of this paper, the publications regarding the simultaneously operating of the satellite service and FS can be divided into two categories: (i) under a clear sky and (ii) under rain condition.

In [9, 10, 12, 17, 18], the clear sky condition was considered at the operating frequency bands for the two systems that are less than 6 GHz (C-band and L-band), while various studies were carried out on higher frequency bands within (17.3–19.7 GHz) [11, 13–16]. All these studies discussed the interference impact on the satellite service from the FS system.

On the other hand, the studies which have considered the impact of rain on operating of the satellite service and FS were reported in [1, 4, 7] which have been carried out in frequencies higher than 10 GHz. The frequencies above 10 GHz are influenced by rain attenuation while the lower frequencies than 6 GHz are not seriously affected by rain attenuation. These studies investigated both impact of the rain attenuation and the interference from the FS on the satellite services.

In terms of the interference protection criterion, most studies depend on the INR, CNIR, and then the CIR ratio whereas some studies depend on the maximum tolerable interference or combine more than one of these criteria.

In terms of rainfall intensity, it can be seen that the study in [8] discusses the intersystem interference in Greece as a Mediterranean region, while the research in [4] investigated the spectrum sharing operation of the satellite and FS services in the tropical region as a heavy rain area. Moreover, the work in [7] studied the satellite and FS services in the semiarid conditions.

Comparing to the previous literature, this paper considers the semiarid area but for various rainfall exceedance probabilities, a stricter interference protection criterion, and various off-axis angles between the DBS receiver and the FS service. The contribution of this paper can be summarized in at least three points, as follows:

- (a) In the current paper, the thermal noise of the DBS receiver has been taken into account, so this study uses the carrier-to-noise plus interference ratio (CNIR) criteria, while in [7], the criterion was different, carrier-to-interference ratio (CIR), as the receiver noise in

[7] was not considered. This makes the current paper more technically sound

- (b) The CIR criterion value in [7] is 23 dB, while this study uses a CNIR of 4.7 dB which adds more restrictions on the receiver ability to pick up the satellite signal
- (c) The study in [4] uses the rain attenuation link budget and the research in [7] applies the rain rate exceedance of 0.01% which does not always occur. Here, various situations of precipitation unavailability percentages (various rain rate exceedance probabilities) which have a high probability to happen especially in the semiarid regions are used. The rain rate exceedances that have been considered in this study are 0.001%, 0.01%, 0.016%, and 0.25%

3. System Protection Criteria

Several criteria can be used to evaluate the feasibility of a system to work in an interference environment to make sure that the system is protected from interference. These criteria are shown in Figure 1. As can be seen in Figure 1, the protection criteria include carrier-to-interference ratio (CIR) and interference-to-noise ratio (INR) which can be defined as a relative or absolute level of interfering signal power determined at the input of the victim receiver, under certain situations, such that the tolerable performance deterioration is not allowed [5, 6]. For acceptable system performance, the necessary CIR is greater than 23 dB [7, 19] and -10 dB for INR [20]. Also, the term carrier-to-noise ratio (CNR) refers to the ratio of signal power to noise power at the receiver output [21]. A CNR > 10 dB is agreed to be a standard value. On the other hand, the nature of the CNIR is due to the impact of the receiver antenna noise added to the interference signal. The CNIR is a significant criterion contributing to the much appropriate precise estimation of the entire outage period of satellite link that suffers from interference lacking any condition concerning the thermal noise. This is an unavoidable condition specifically for systems operating within an interference environment as a dominant factor [21, 22]. In [22], it is stated that the necessary CNIR is 4.7 dB for DBS to operate with satisfactory performance. As a result of both the interference (I) from the FS and the receiver thermal noise power (N) of the DBS receiver, the CNIR (dB) can be estimated by equation (1) [23, 24] as follows:

$$\frac{C}{(N+I)} = -10 \log \left(10^{-0.1(C/N)} + 10^{-0.1(C/I)} \right), \quad (1)$$

where C is the carrier power of the satellite transmitter at the DBS receiver.

As can be seen from the literature work in Section 2, all performance metrics are previously used for spectrum sharing studies. The CNIR is a significant measure performance, and in this paper, the sharing performance criteria of the CNIR are selected due to the following characteristics:

TABLE 1: Relevant prior work summarizing.

Ref.	Frequency band	Weather condition	Sharing criteria	Shared systems	Remarks
[8]	>10 GHz	Rainy (Mediterranean region)	CNIR	BSS and FS	It presents a model for CNIR prediction of a BSS downlink interfered by an adjacent FS. It focuses on the additional outage time caused by rain fading on the wanted satellite slant path and the interfering terrestrial path.
[9]	3.8 GHz	Clear sky	INR	5G and FSS	It estimates the protection distance to satisfy the protection criterion between the FSS and the 5G system with relation to elevation angle and antenna pattern.
[10]	3.4–4.2 GHz	Clear sky	INR and the maximum tolerable interference	5G and FSS	It presents the impact of out-of-band emissions and potential low-noise block (LNB) saturation at the FSS Earth station receiver and the consequences of the deployment of active antenna systems in the terrestrial FS.
[11]	17.7–19.7 GHz	Clear sky	INR	FSS and FS	Various sensing and avoidance schemes have been proposed for allowing the coexistence of FSS downlink with the terrestrial FS links.
[12]	3.5 GHz	Clear sky	INR	FSS and small cell FS	It estimates the protection distances required to protect FSS Earth stations from the FS for the case when small cells are deployed indoor and outdoor.
[13]	17.7–19.7 GHz	Clear sky	CNIR	FSS and (BSS and FS)	Spectrum databases for BSS and FS systems have been used to estimate CNIR based on a cognitive basis to increase the overall throughput.
[14]	17.3 to 17.7 GHz	Clear sky	The maximum tolerable interference	FSS and (FS and BSS)	Interference from BSS and FS is estimated using real databases and propagation models using correct terrain profiles. Some operational challenges are also discussed.
[15]	18.8–19.7 GHz	Clear sky	INR	GSO network and terrestrial network	It estimates the minimum separation distances between the geostationary satellite Earth station and the terrestrial FS in the worst case.
[16]	17.3–18.4 GHz	Clear sky	INR	FSS and BSS	It studies the effect of the elevation angle on the sharing between the BSS and FSS Earth stations with/without shielding in FSS/BSS terminals. The sharing is highly feasible with proper protection zones around stations.
[17]	2.185 GHz	Clear sky	CIR	MSS and MS	It estimates sharing between the mobile satellite service (MSS) system and the mobile service (MS) system. Sharing is hardly feasible in a cochannel frequency and collocated situations.
[18]	3.4–4.2 GHz	Clear sky	INR	FSS NWs and IMT2000	It investigates the sharing between the FSS networks (with low and high density of deployment) and IMT 2000.
[4]	21.4–22 GHz	Rainy (tropical region)	CNIR and INR	DBS and FS	It investigates the sharing between the DBS and FS services with the rain attenuation link budget. It is found that the denser the clutter area, the lower the interference introduced to the wanted system.
[7]	21.4–22 GHz	Rainy (semiarid region)	CIR	DBS and FS	It investigates the sharing between the DBS and FS services for rain rate exceedance of 0.01% only. The protection distance between the systems can be affected by changing the height of DBS ES.
This paper	21.4–22 GHz	Rainy (semi-arid region) various rain rate exceedance probabilities	CNIR	DBS and FS	It investigates the sharing between the DBS and FS services with various precipitation unavailability percentages which have high probabilities to happen especially in the semiarid regions. Various off-axis angles are employed.

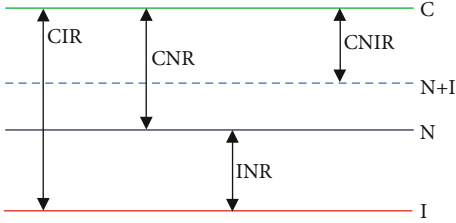


FIGURE 1: Protection criteria levels at communication receivers.

- (a) Indicating equation (1), it can be seen that the CNIR depends on the CNR and CIR ratios. In addition, CIR in turn depends also on the INR ratio [8]: C/I (dB) = C/N (dB) - I/N (dB) this means that the CNIR criteria implicitly include all performance metrics
- (b) The CNIR has been used in many studies, such as [25] which concluded that at the frequency bands (Ku, K, and Ku), the interference problem of adjacent satellites, essentially clear for spotbeam/cell edge terminals, becomes more exacerbated by propagation effects, mainly attenuation by rain. In addition, the CNIR is of supreme significance in the design of new satellite broadband systems based on digital video broadcasting (DVB)
- (c) In cellular systems for example [26], the probability distribution of the CNIR has a significant task in performance evaluation of the system, managing of the radio resource, and planning of the radio network. Thus, a precise probability density function (PDF) of CNIR leads to effortlessly predicting of the capacity and coverage of the system; otherwise, time-consuming and sophisticated simulations should be used
- (d) Generally, recent development of multiple input multiple output (MIMO) beamforming techniques creates a new dimension for cochannel users to coexist without causing severe interference to each other. In conventional methods, beamforming is obtained by either maximizing the carrier-to-interference plus noise ratio (CNIR) or minimizing the transmission energy subject to a minimum CNIR constraint [27–30]

4. Rain Distribution

A lot of rain effect studies have been conducted in different frequency bands such as in [31–34] in a tropical region. The Kingdom of Saudi Arabia map is distributed into five climate regions which can be described as a semiarid region. Therefore, the available measured instantaneous rain rate distributions were pooled for each of the climate regions [2, 35]. According to Table 2, the findings indicate that the southwestern side of Saudi Arabia has higher rain rates and the north side has lower rainfall rates. Thus, five locations have been selected to classify rain climate regions for

TABLE 2: Measured rainfall rate readings and calculated attenuation for the selected locations.

Climate regions	Tabuk	Riyadh	Makkah	Abha	Al Bahah
$R_{0.01}$ (mm/h)	9.71	17.17	27.92	37.24	53.10
$A_{0.01}$ (dB)	12.07	25.478	39.6	52.74	76.6
$R_{0.016}$ (mm/h)	7.65	13.53	21.85	29.27	40.47
$A_{0.016}$ (dB)	8.758	18.32	29.114	39.13	54.94
$R_{0.001}$ (mm/h)	31.20	55.09	92.74	121.07	200.95
$A_{0.001}$ (dB)	37.408	78.13	129.59	169.583	287.58

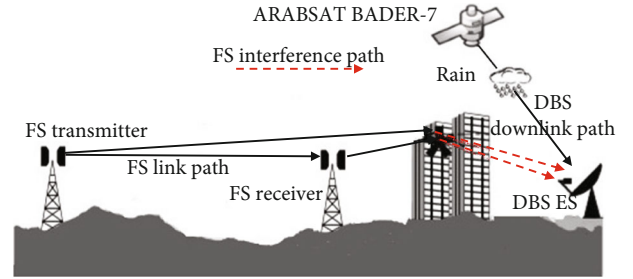


FIGURE 2: The proposed arrangement between an interfered downlink signal (DBS) which suffers from rain and FS interference in different propagation environments.

the Kingdom of Saudi Arabia reliant on weather circumstances which in turn rely upon longitude and latitude locations. These locations are Riyadh in the middle (2), Makkah in the west (3), Abha in the south (4), Al Bahah in the southwest (5), and Tabuk in the north (1). These areas are distributed on diverse sides in Saudi Arabia characterizing different rainfall rates based on weather circumstances and different longitude and latitude. According to ITU-R recommendations, a link availability of 99.99% was selected to denote the intensity of rainfall (mm/h) of 0.01% probability of rain incidence on a specific place serviced by a wireless system. This percentage represents 52.56 minutes/year of outage time.

5. Methodology and Proposed Scenarios

As shown in Figure 2, a DBS Earth station (ES) receiver and FS operate in a close area. In this scenario, both systems use the 21.4–22 GHz band, with an identical carrier frequency of 21.728 GHz which can create an imperative interference. It is supposed that an ES receiver of the direct broadcasting service (the desirable link) is deleteriously saturated by the signal from an FS system. The interfering can influence the downlink desired signal in both clear-air and rainfall. Whereas, a 21.728 GHz carrier frequency of the DBS signal (horizontally polarized) is directed from the 26°E geostationary orbit ARABSAT BADER-7 into 5 ESs assumed to be situated at the five selected locations in Saudi Arabia. Thus, depending on the specification of two systems, the effect of the interference is certain in clear air and rainfall (worst case). Additionally, the impact of rain attenuation and the receiver antenna noise on the reception quality is evaluated. The simulation is built upon real values related to the DBS

TABLE 3: The main key spectrum sharing assumptions and parameters [7, 36].

Parameters	DBS	Value	FS
Carrier frequency (MHz)		21728	
ARABSAT Bader-7 longitude (E)	26		—
DBS ES receiver sensitivity (clear sky) (dBW)	-119.566		—
Gain of receiver antenna (dBi)	56.6557		34.8
EIRP ES (dBW)	34.2		—
Free space path loss (dB) from satellite to earth station	210.4		—
Saudi Arabia rain height (m)		5400	
Receiver antenna height above mean sea level (km)	0.1		0.15
Bandwidth (MHz)	11.6580		7
Bandwidth of noise (MHz)	8.6356		7
Off-axis angle of antenna (°)	3		—
Diameter of receiver antenna (m)	3.7		0.6
Interferer power of FS (EIRP) (dBW)	—		-146.6

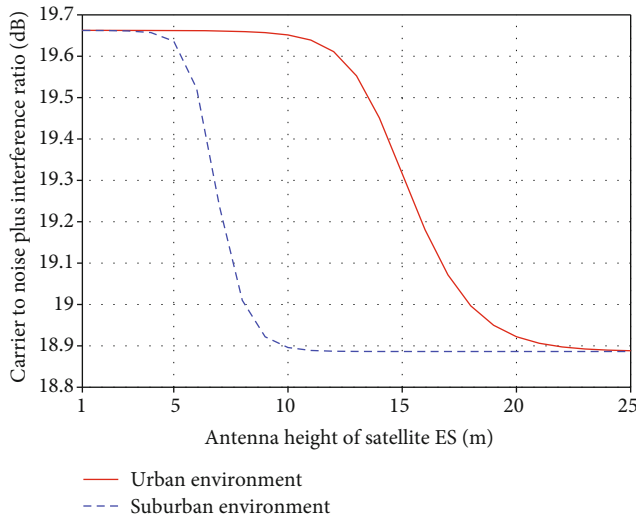


FIGURE 3: The receiver CNIR against the antenna height of the DBS receiver under clear sky condition.

service obtained from the Arab Satellite Communications Organization (ARABSAT), the satellite service provider in Saudi Arabia. Moreover, the five selected locations look to ARABSAT BADER-7 by diverse elevation and azimuth angles and FS parameters are based on [36]. The scenario shown in Figure 2 is applied to the five different selected locations over Saudi Arabia which are shown in Table 2. Further, clutter loss is considered within this scenario which is contributing to limit the interference power (unwanted power) depending on the Earth station antenna height and the nature of the area.

The CNIR level is evaluated in different propagation environments for all selected locations under a clear sky and rain conditions over which two different area categories (urban, suburban). Due to the fact that each area has dissimilar clutter features that can cause a definite loss to the interfering signal [37–40]. The received downlink signal, P_r

(watt), at the DBS receiver can be evaluated by using equation (2) as follows:

$$P_r = P_t G_t G_r \left(\frac{4\pi d}{\lambda} \right)^2, \quad (2)$$

where P_t is the transmission power (watt) from the satellite in the sky, G_t is the satellite transmission antenna gain, G_r is the antenna gain of the DBS Earth station (DBS receiver), d is the physical path between the DBS receiver and satellite (km), and λ is the operating wavelength in (m). The free space loss L_{fsl} given by equation (3) as follows:

$$L_{fsl} = \left(\frac{4\pi d}{\lambda} \right)^2. \quad (3)$$

Then, the specific attenuation, γ_R (dB/km), is calculated and relied on real measured quantities of rain, $R_{0.01}$ (mm/h) and values of k and α , which are functions of frequency, f , and polarization specified in ITUR P.838, as follows [28]:

$$\gamma_R = k(R_{0.01})^\alpha. \quad (4)$$

The rain attenuation, $A_{0.01}$ (dB), is given by equation (5) as follows:

$$A_{0.01} = \gamma_R L_E, \quad (5)$$

where L_E is the effective path length (km).

The local clutter can cause extra losses that affect the interference path since it can block the signal, this loss is denoted by L_C , and thus, its amount contributes to the entire interference power. This loss is expressed as follows [37] in (6), where h is the antenna height above the local ground

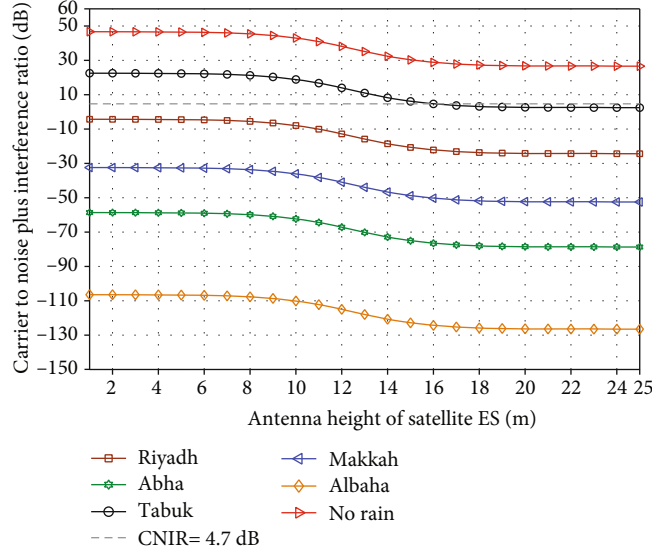


FIGURE 4: The CNIR against ES antenna height (urban area).

level, h_a is the nominal clutter height above the local ground level, and d_c is the distance from the nominal clutter point to the antenna.

$$L_C = 10.25e^{-d_c} \left(1 - \tanh \left(6 \left(\frac{h}{h_a} - 0.625 \right) \right) \right) - 0.33. \quad (6)$$

The nominal distance and nominal clutter height for the urban area are 20 m and 0.02 km, respectively, whereas these values for the suburban area are 9 m and 0.025 km, respectively [4].

6. CNIR and Communication Link Simulation

A MATLAB code has been created to simulate the CNIR and the communication links in which the environment of the satellite communication system link has been installed by defining the main connection link parameters that contribute to the computing of the carrier power (C) at the DBS receiver. These parameters include (a) the DBS satellite transmitter, (b) the gain of the DBS receiver (earth station) antenna, and (c) the propagation channel parameter effects which are mainly represented by (i) rain phenomena (by equations (4) and (5)), (ii) clutter loss (by equation (6)), and (iii) free space attenuation loss (by equation (3)). Then, all these parts are integrated into the satellite communication link environment as equation (1), where all factors will contribute to the carrier signal (C) at the DBS receiver as in equation (7), as follows:

$$C \text{ (dB)} = P_r - A_{0.01} - L_C. \quad (7)$$

Next, the effect of the interference link coming from the FS system as well as the noise parameters of the receiver is added together and computed to give the total effect of the interference (I) and thermal noise power (N), which is $N + I$, as in equation (1). Finally, a comparison between the

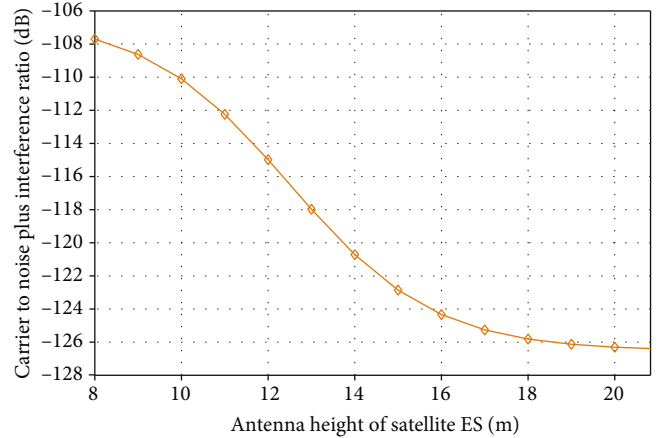


FIGURE 5: Magnification of Figure 4: the CNIR against the ES antenna height in Al Bahah (urban area).

CNIR resultant from the simulation and the CNIR criterion is made to determine whether the DBS receiver can receive the signal from the satellite with good performance or not.

7. Assumptions, Results, and Discussion

Table 3 describes the key factors for the considered systems (DBS ES and FS transmitter). The distances between the FS transmitter and the DBS Earth station receiver are considered as one of the coexistence limitations. Thus, the CNIR was investigated through distances of 1 to 50 km which can be assumed to be a line-of-sight (LOS) case.

In Figure 3, two deployment areas (urban and suburban) under a clear sky are shown with CNIR criteria in terms of the DBS receiver antenna height. It can be observed that the CNIR has not much difference in the CNIR for both the urban area and the suburban area; that is, changing antenna height by 18 m height from 4 to 22 m makes only a difference in a CNIR of 1 dB. Therefore, we can say that

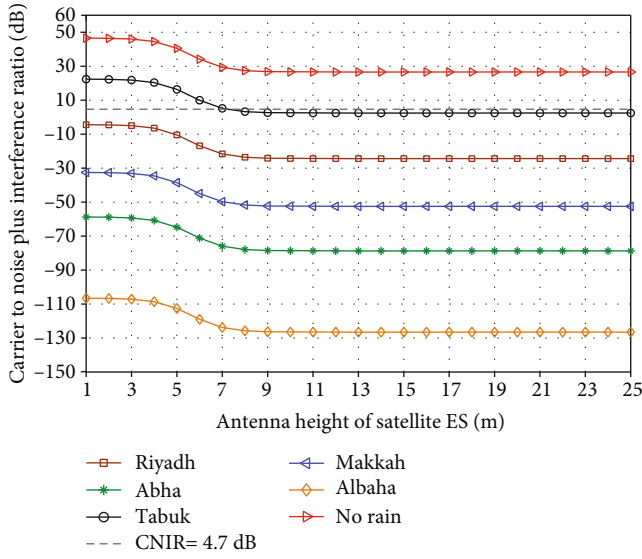


FIGURE 6: The CNIR against ES antenna height (suburban area).

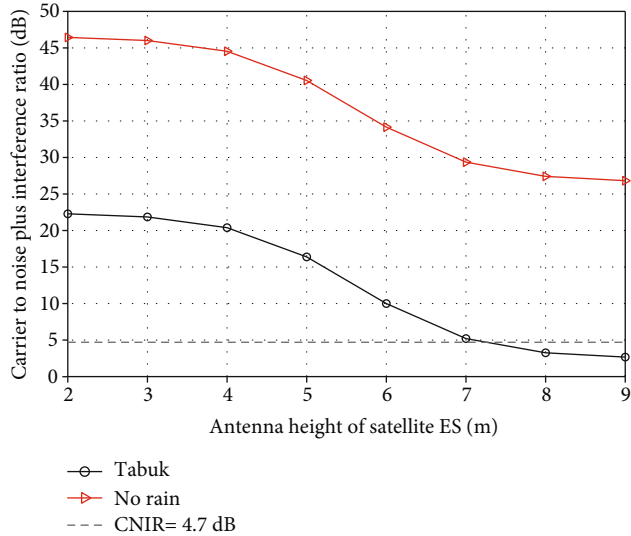


FIGURE 7: Magnification of Figure 6: the CNIR against the ES antenna height in Al Bahah (Suburban area).

changing the antenna height in these two areas is not an efficient technique. However, the DBS system receiver works peacefully in both areas because the required ratio of the CNIR is about 18.9–19.7. That is, it is achieved and greater than the minimum level of 4.7 dB. Note that the receiver sensitivity signal has been adjusted for all selected locations at -119.566 dBW.

Several scenarios have been carried out to investigate the received signal in terms of the CNIR in the five areas of Saudi Arabia for the availability of rain of $R_{0.01}$ of the year and using different heights of the receiver antenna of the DBS system as can be shown in Figures 4 and 5 for the urban and suburban areas, respectively. Figure 4 shows that Al Bahah is the worst area that suffers from the attenuation of rain; therefore, the CNIR is the lowest level especially for antenna heights between 10 and 20 m. The value of the

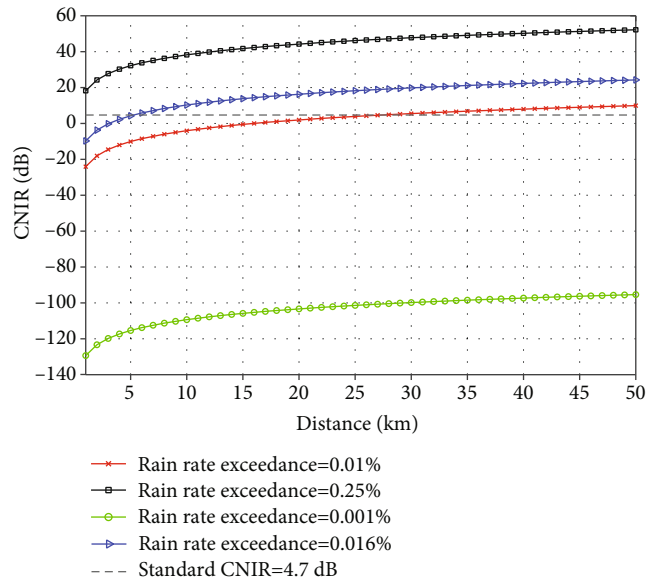


FIGURE 8: The receiver CNIR due to rain in Riyadh.

CNIR is about -110.1 to -126.3 dB for the height of 10–20 m, as shown in Figure 6. Also, it can be observed in Figure 4 that before and after the abovementioned heights, the ratio of the CNIR is fixed. The decrease in the CNIR during that height is because as the antenna height of the DBS receiver increases, the interference signal level coming from the fixed wireless system does not face the surrounding objects to block the radiated signal (low clutter loss) in its path so the interference raises and the CNIR will be a low value and then the performance is worse. On the other hand, it can be observed that the Tabuk area does not suffer from interference if the DBS receiver antenna height is lower than 18 m because the CNIR is larger or at least equal to 4.7 dB. Moreover, the DBS system receiver in the other areas, Riyadh, Makkah, and Abha, negatively works during rain situations due to the degradation in the satellite signal and then the lower value of the CNIR. However, Figure 4 illustrates that the situation of the clear sky condition (no rain) is the best situation and the DBS receiver system can operate in any area because the signal arrives at the DBS receiver with a highly enough CNIR ratio.

Figure 5 illustrates the situation for the five areas under precipitation in the suburban environment. This area is characterized by an open atmosphere more than that of the urban areas. Unlike urban areas, in suburban areas, there are no tall and congested buildings or towers that can block communication signals. Therefore, the interference effect will be high in these areas and this is obvious in Figure 7, in which it is shown that a small increase in the height of the DBS receiver antenna from 4 m to 8 m can raise interference and decrease the CNIR by roughly 17 dB. That is, for the same change of antenna height (4–8 m), as shown in Figure 7, the value of the CNIR decreases from 20.4 dB to 3.3 dB in Tabuk which is the only area that can well operate in this situation. In the case of the antenna height increase by more than 7.3 m, the system will suffer from an acceptable interference and will not work. The former situation is

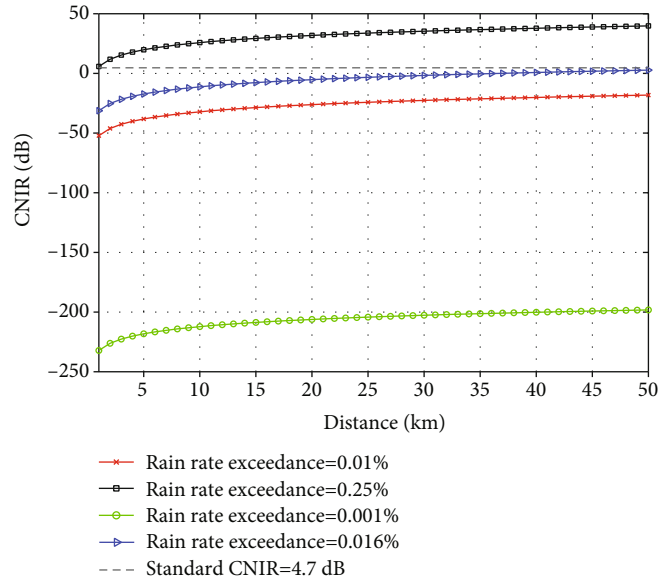


FIGURE 9: The receiver CNIR due to rain in Makkah.

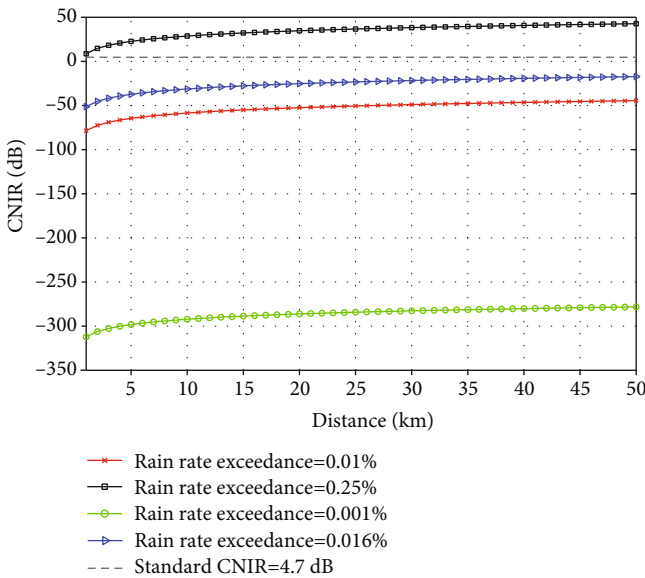


FIGURE 10: The receiver CNIR due to rain in Abha.

the case for the other areas except Tabuk where the conditions does not allow the DBS system to operate because the CNIR value is smaller than 4.7 dB even for very low antenna heights. Figure 6 also illustrates that in the no-rain case, the system will work with high performance for all areas.

More values of precipitation unavailability percentage have been considered for this study, the values are 0.25, 0.001, and 0.016% in addition to 0.01%. These conditions have been applied to all the abovementioned geographical areas. In the capital city, Riyadh, as illustrated in Figure 8, the DBS system receiver works with acceptable performance at a rain rate that exceeded by 0.25% of the year, whereas at rain rates of 0.01% and 0.016%, the DBS system receiver needs a guard distance of 5 and 24 km, respectively, to oper-

ate without the negative effect of interference of the terrestrial fixed service. However, at a rain rate that exceeded by 0.25% of the year, the DBS system receiver cannot properly operate if the interference or rain mitigation techniques have not been used. It can be noted that the rate of change in the CNIR is about 0–35 dB within the distance of 1–50 km for all areas.

In the area of Makkah, as shown in Figure 9, the situation is approximately similar to Riyadh at a rain rate that exceeded by 0.25% of the year, in which there is no need for a protection distance despite that the CNIR value is higher in Riyadh than in Makkah by approximately 20 dB. However, it is worse than Riyadh for a rain rate more than that percentage. That is, the required minimum protection distance is roughly 50 km at a rain rate that exceeded by 0.01%, whereas the DBS system receiver cannot work at the other two rain rates, 0.016% and 0.001%, due to the large decrease in the CNIR value which is caused by the higher rain rate in Makkah than Riyadh.

In Abha and Al Bahah, the situation is more difficult than that in Riyadh and Makkah due to the high attenuation of rain caused by high rain rates. In both areas (Abha and Al Bahah), it can be seen in Figures 10 and 11 that the DBS system receiver can only peacefully operate at a rain rate that exceeded by 0.25% of the year. Whereas, the other exceedance of rain rates 0.01%, 0.016%, and 0.001% makes the system in an outage condition due to high negative CNIR values that come from a high rain rate specifically in the Al Bahah area. For example, at a rate of 0.01%, the CNIR is -18 and -55 dB at a separation distance of 50 km between the DBS receiver and the fixed wireless system; the late values become much lower at the 50 km distance between the two abovementioned systems in both areas.

For the Tabuk area, the DBS system receiver operates better than that in the other areas due to the fact that the CNIR value represents the best among CNIRs in other areas for all situations. Figure 12 shows that the DBS receiver will

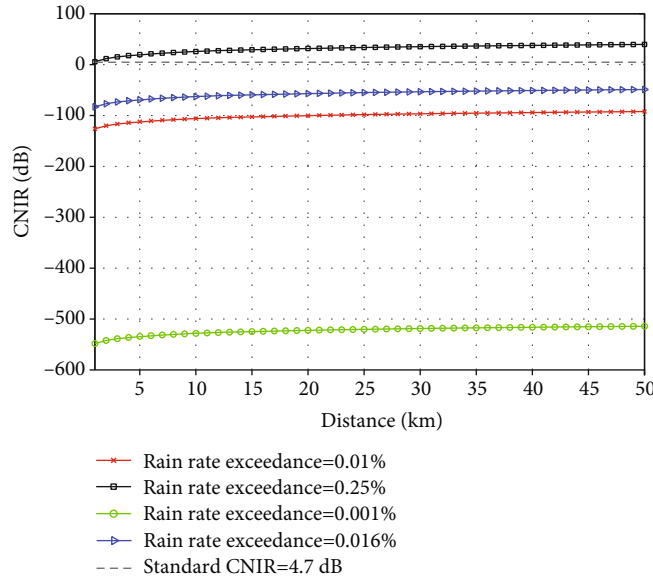


FIGURE 11: The receiver CNIR due to rain in Al Bahah.

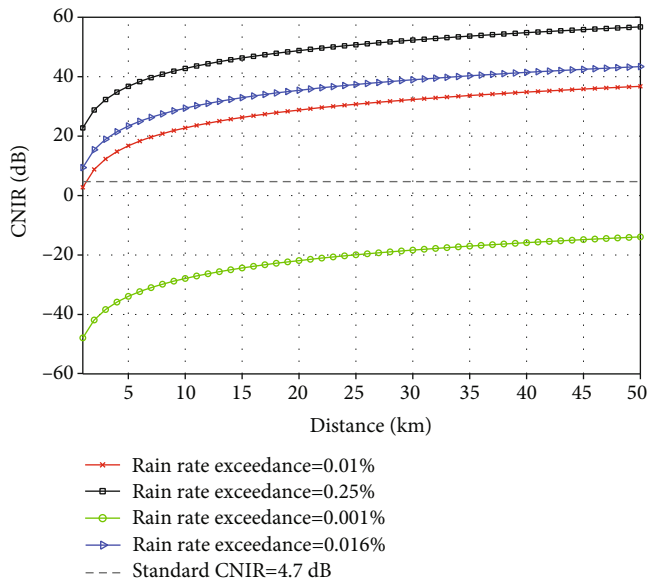


FIGURE 12: The receiver CNIR due to rain in Tabuk.

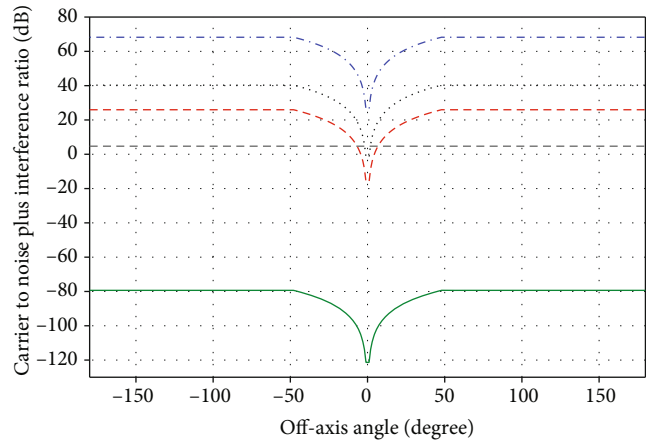


FIGURE 13: CNIR vs. the off-axis angle of Riyadh at 10 km between the FS and DBS receiver.

operate under a rain rate exceedance of 0.25% and 0.01% with no protection distance to avoid interference from the terrestrial fixed wireless system. While for a rain rate exceedance of 0.016% for both systems to work properly, there is a need to make a separation distance of 1.3 km between the DBS and fixed service. However, the system will absolutely not operate for 0.001% without using coordination techniques to prevent interference from the fixed service or techniques to raise the power received by the DBS receiver.

Moreover, the possible interference power that can be received from the terrestrial FS interferer is partially dependent on the DBS ES antenna gain in the direction of the terrestrial FS interferer. This effect can be termed as the off-axis angle or the off-boresight angle [41]. The off-axis angle is

defined as the angle between the interference axis and the DBS ES antenna main lobe direction [41]. Figures 13–17 show the effect of the off-axis angle between the DBS satellite Earth station and the FS transmitter that is assumed to be 10 km apart.

It is observed in Figures 13–17 that there is a significant impact of the off-axis angle particularly for the low-rain rate areas. The values of the CNIR for all areas increase as the off-axis angle increases till it reaches 48° , and then, CNIR values stay constant according to the satellite antenna pattern. In Figure 13, the curves show that the two systems (FS and DBS ES) can operate with no interference harmful for a rain exceedance of 0.25% for all off-axis angles, whereas for rain rates of 0.016% and 0.01%, the two systems cannot work

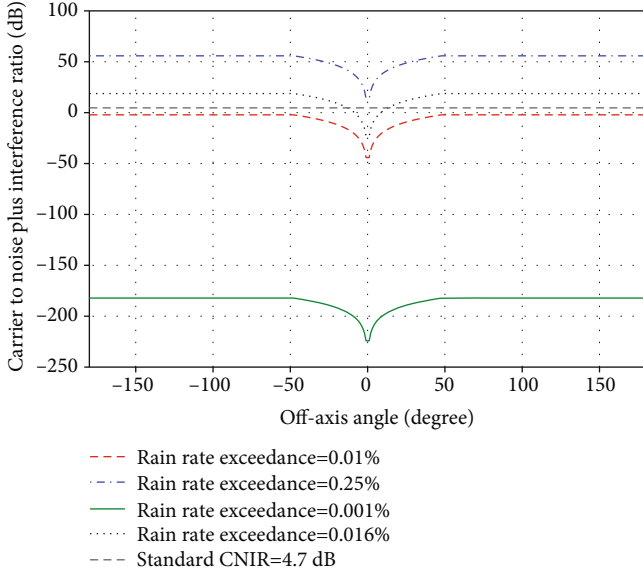


FIGURE 14: CNIR vs. the off-axis angle of Makkah at 10 km between the FS and DBS receiver.

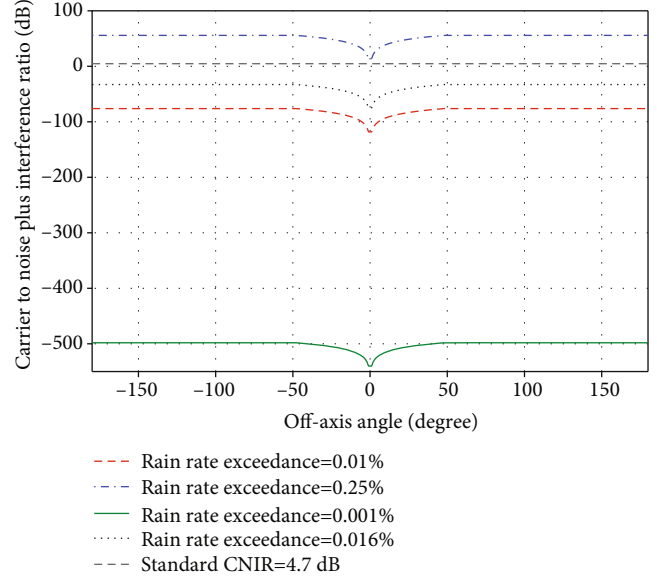


FIGURE 16: CNIR vs. the off-axis angle of Al Bahah at 10 km between the FS and DBS receiver.

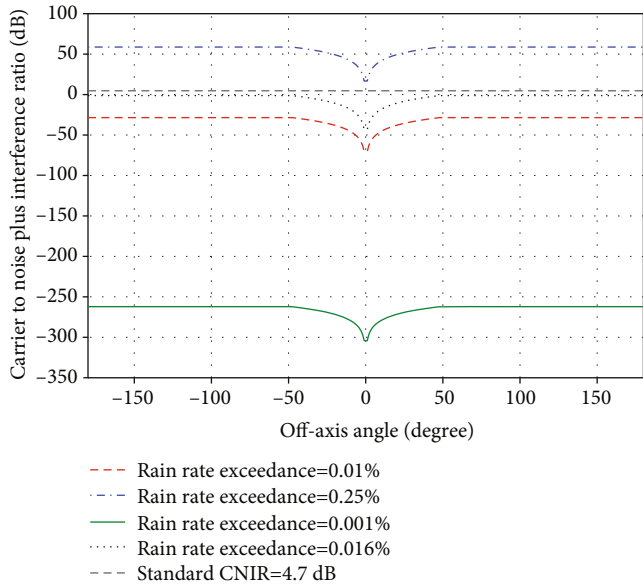


FIGURE 15: CNIR vs. the off-axis angle of Abha at 10 km between the FS and DBS receiver.

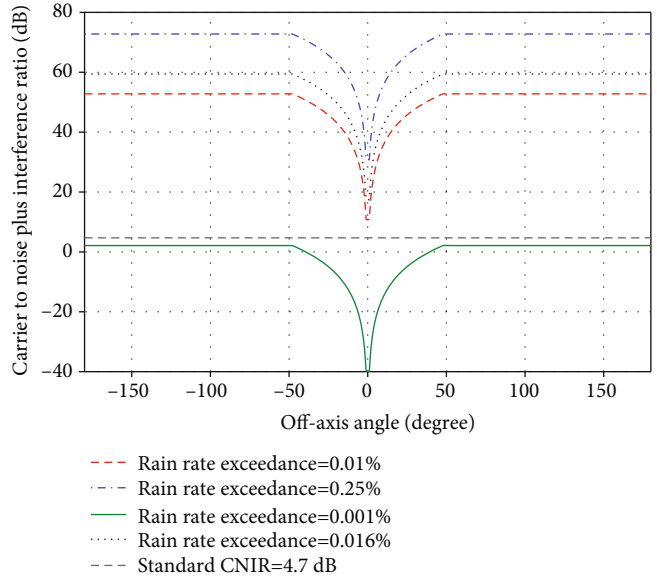


FIGURE 17: CNIR vs. the off-axis angle of Tabuk at 10 km between the FS and DBS receiver.

together if the off-axis angles are less than $\mp 1.58^\circ$ and $\mp 6.77^\circ$. Also, in the Makkah area, an angle of $\mp 13.1^\circ$ between the FS and DBS ES is required for a rain rate exceedance of 0.016% for the concurrent operation, while the systems cannot simultaneously function if the rain rate is heavier (with an exceedance of 0.01 and 0.001%). The situation in Abha and Al Bahah seems comparable regarding the off-axis influence, and the frequency sharing is only possible for the lowest rain rates (0.25% exceedance) while it is impossible for the other rates taking into account the difference in values of the CNIR. Finally, Tabuk seems to be the best area for the two systems to simultaneously work with no considering off-axis coordination at 0.25%, 0.016%, and 0.01% exceedance;

however, at an exceedance of 0.001%, the concurrent work is not feasible.

From the abovementioned analysis, it can be concluded that coordination using an off-axis angle makes a difference in the case of medium rain rates (0.016 and 0.01%) as in Riyadh and Makkah as shown in Table 4 which summarizes the effect of the off-axis angle variation.

The authors believe that the results predicted in this paper can replace or reduce the requirements for physical measurements due to the fact that the results depend on real and measured rainfall data and the simulation method is authorized by the ITU-R as a global body of communication organizing [40]. In addition, this model [40] has been widely

TABLE 4: The effect of the off-axis angle.

Exceedance	Tabuk	Riyadh	Makkah	Abha	Al Bahah
0.25%	All angles	All angles	All angles	All angles	All angles
0.016%	All angles	$>\mp 1.58^\circ$	$<\mp 13.1^\circ$	No	No
0.01%	All angles	$>\mp 6.77^\circ$	No	No	No
0.001%	No	No	No	No	No

used by many researchers over the world such as in [42–44], in which the results are of global acceptability.

8. Conclusion

This paper introduced significant results on the operation of the DBS receiver under the influence of precipitation and interference from the FS service at the K-frequency band. The results showed that the rate of change in the CNIR is about 0–35 dB within the distance of 1–50 km for all areas under the study. The conditions in the Al Bahah area represent the most worse area in the entire region, whereas Tabuk represents the best area that can work properly in most cases under rain rates with less restriction due to the lower and higher values of the CNIR of the DBS receiver in both areas. Similar restrictions on the CNIR, separation distance, frequency separation, and so on can be also applied to different countries with similar precipitation circumstances. Modifying the off-axis angle to coordinate the DBS and FS systems can reduce the interference from the FS system especially when the CNIR threshold is within the off-axis angle varying range as in Riyadh and Makkah areas. Several techniques also can be suggested to use in critical situations under high rainfall such as automatic gain control (AGC) and/or adaptive modulation techniques. In addition, the interference coming from the wireless terrestrial system to the DBS receiver can be avoided by adjusting the feasible required physical distance.

Data Availability

The rainfall data used to support the findings of this study are included within the article and cited references.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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