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RESEARCH ARTICLE

Sharing and Compatibility Studies for IMT and DTTB Systems in the Sub-700 MHz UHF Band

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ABSTRACT In this paper, we present a simulation-based study for the coexistence of an International Mobile Telecommunication (IMT) system with a Digital Terrestrial Television Broadcasting (DTTB) system. The study considers the coexistence of the two systems in the sub-700 MHz band and presents interference analysis results for locations in the Kingdom of Saudi Arabia (KSA). The study includes different terrains in which each of the two systems is deployed, e.g., mountains, sea, desert, etc. Using an advanced terrain-aware simulation software (HTZ from Advanced Topographic and Digital Imaging (ATDI), the coexistence problem is studied in these cases which represent some of the most common types of terrains. The goal is to quantify the level of interference in each of the case studies and compare it with the protection ratio in terms of either the carrier-to-interference-plus noise $C/(I+N)$ or interference-to-noise (I/N) ratios, depending on the simulation parameters and following the standard approach used in such studies. These two measures help in providing the proper recommendations on the coexistence of the IMT and DTTB systems. This study is structured into two main parts. The first part focuses on studying the interference induced by IMT base station (BS) and IMT user equipment (UE) on the DTTB receiver in the sub−700 MHz band (from 614 to 694 MHz) which corresponds to the 5G N71 band, whereas the second part considers the interference induced by DTTB system on IMT BS and IMT UE. The investigation has revealed that in most of those situations, separation distances (exclusion zones) are found to be relatively within a reasonable range from the border compared with the size of the whole network. This indicates that IMT network could be deployed in many locations close to the DTTB network with tolerable effect. The most challenging case is the effect of DTTB system on the up-link (UL) of IMT network, which necessitates the use of additional mitigation techniques to reduce the interference.

INDEX TERMS Digital divide, DTTB, IMT, RF spectrum coexistence, 5G N71 band, sub−700 MHz.

I. INTRODUCTION

Wireless communication systems are instrumental to various emerging technologies such as the Internet of Things (IoT), virtual reality (VR), augmented reality (AR), and autonomous driving [1], [2], [3]. Collectively, these technologies rely on wireless systems in their operation, and, as such, they are driving a surge in demand for wireless services, which translates into increasing demands for data rates. Spectrum regulatory bodies such as the

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Communications, Space & Technology Commission (CST) in the Kingdom of Saudi Arabia (KSA), plan to meet those demands by bolstering the share of the spectrum allocated to these services/systems.

In recent research work, the coexistence between different wireless networks sharing the same frequency band has been studied. For instance, in [4] and [5], a survey of the coexistence techniques and mechanisms used in various wireless technologies is presented. Moreover, further papers analyzed the coexistence between different wireless networks that share the same spectrum, and provided recommendations to minimize the interference between these networks. For example, [6] analyzed the coexistence between International Mobile Telecommunications (IMT) systems and fixed wireless access services in the 790-862 MHz band. In particular, Spectral Emission Mask (SEM) was used to build a mathematical model to study the impact of several factors, such as channel bandwidth and clutter loss, on the interference between the two systems. Based on these results, the paper recommended mitigation procedures to minimize the interference impact, including specifying a coordination distance and frequency separation between the two networks. Similarly, [7] analyzed the coexistence between Digital TV (DTV) services and Television White Spaces (TVWS). The paper presented the required coordination distance between two systems based on an analytical mathematical model including the impact of the antenna height.

Several prior papers studied the coexistence between cellular networks and Digital Terrestrial Television Broadcasting (DTTB) in the Ultra-High Frequency (UHF) band. This direction has gained traction since roughly the mid-2000s, where a decline in demand for DTTB services has been identified [8]. The decline has resulted in the re-allocation of the upper side of the UHF spectrum (roughly 700 to 870 MHz) in the late 2000s to the IMT services [9], and has sparked growing interest in further spectrum-utilization studies. For instance, in [10], the co-channel interference between the two systems is analyzed by evaluating the degradation in the receiver performance using Monte Carlo simulations for multiple separation distances. In addition, [9] studied the impact of the LTE base-stations and user-equipment on DTTB receivers in the 700 MHz band. The paper presented the required measured protection ratios to operate DTTB receivers for various data-rates, signals bandwidths, and output powers. However, all these previous studies rely on generic models to estimate the interference between the two networks. The use of such models might not often be sufficient to perform the required coexistence analysis since it does not account for the impact of clutter and terrain, which can change the outcome significantly. On the other hand, utilizing a terrain-aware software, like what is used in this study, takes into consideration the Geographic Information System (GIS) data of the terrain and clutter in the calculation of the received power. The precision of the map can go up to 20 meters in KSA and gulf countries. Using terrain-aware software was demonstrated in [11] to analyze the coverage of the DVB-T2 network but not the impact of interference on its performance.

Several technical reports were presented by the International Telecommunication Union (ITU) to analyze the required separation distance between the IMT and DTTB systems. In [12], the needed separation distance to protect the DTTB network from IMT induced interference is pretested. The distance is calculated based on generic models without analyzing the terrain type impact. Moreover, another report [13] documented various national level field measurements in the 700 and 800 MHz bands. The report included the field strength measurements at certain distances for real-world interference cases.

The digital dividend band, spanning from 614 to 694 MHz, brings revolutionary potential to International Mobile Telecommunications (IMT). This relatively low-frequency band, which corresponds to the 5G N71 band, permeates through buildings, hills, and dense urban environments far more efficiently than higher frequencies. It provides widespread and reliable coverage with fewer cell sites, lowering the infrastructural costs and thus improving affordability. Moreover, the robustness against interference improves the quality of service, bringing us closer to the promise of seamless mobile broadband. When applied to IMT, the digital dividend band could stimulate unprecedented growth in rural and remote areas, which often suffer from a lack of reliable connectivity. This can drive socio-economic growth by enabling access to essential digital services like e-learning, telemedicine, and e-commerce. For urban areas, it can alleviate network congestion, significantly improving data speeds and connection stability, crucial for emerging technologies like autonomous vehicles and Internet of Things (IoT) applications.

On the other hand, the trend of decreasing reliance on Digital Terrestrial Television Broadcasting (DTTB) signals a significant shift in the media landscape, which is consequently leading to a decline in the necessity of its associated Radio Frequency (RF) spectrum. This decline is largely propelled by the rapid digital transformation and the emergence of broadband internet services. Increasingly, consumers are gravitating towards over-the-top (OTT) platforms, as well as Internet Protocol Television (IPTV) services, which provide a more personalized and flexible consumption experience. These platforms offer high-definition, on-demand content and interactive services that far exceed the capabilities of DTTB, causing a significant shift in viewer preferences.

In this paper, we study the sharing and compatibility between the DTTB and IMT systems in the UHF band, specifically within the band 470 MHz to 694 MHz [14], [15], using an advanced clutter and terrain-aware software. In particular, we investigate the coexistence between the IMT and DTTB systems in the sub−700 MHz band (from 614 to 694 MHz). This band is part of the 5G new radio (NR) standard, specifically the N71 band [16]. The importance of this band with respect to higher frequency bands is that the signal can travel for longer distances thus covering larger areas and enhancing the connectivity in rural areas. In a more advanced scenario, carrier aggregation between the low and mid bands can be done [16], which permits the combination of the rates from the two bands.

The investigation targets providing insights on whether or not the coexistence between the IMT and DTTB systems is possible, in addition to providing takeaway recommendations for practical implementation. It does so by considering case studies representing various locations in KSA with different terrains (land, sea, mountains). The IMT and DTTB systems are simulated using an advanced clutter and terrain-aware software simulator. The investigation has revealed that in most of those situations, separation distances (exclusion zones) are found to be relatively within a reasonable range. This indicates that IMT network could be deployed in many locations close to the DTTB network with insignificant effect. The most challenging case is the effect of DTTB system on the Up-Link (UL) of IMT network, which necessitates the use of mitigation techniques to reduce the interference.

The remainder of the paper is organized as follows. Section II presents the system model, study parameters, and the methodology followed to produce the results of this research work. Section III provides the effect of IMT system on DTTB service. Section IV shows the effect of DTTB system on IMT service. Finally, Section V concludes the paper.

II. SYSTEM DESCRIPTION

This paper investigates the impact of deploying an IMT system close to a DTTB system, where the investigation is divided into two parts:

- Part I: Interference induced by a group of IMT Base Stations (BSs) and User Equipment (UE) on DTTB receivers, as illustrated in Figure 1a and detailed in Section III.
- Part II: Interference induced by a DTTB transmitter on IMT BSs and UE, as illustrated in Figure 1b and detailed in Section IV.

The interference is quantified using ''separation distance'' or ''exclusion zone'' between DTTB transmitters and an IMT BS/network, which is a common measure in the International Telecommunication Union (ITU) community [12], [17]. The study provides simulation results for interference scenarios with different terrains (land, sea, mountains) and different environments (rural, urban), using a terrain-aware software. The separation distance is defined in this paper to be the minimum distance separating the virtual border and the nearest IMT base-station that allows the two systems to coexist in the same frequency band.

A. STUDY PARAMETERS

Each simulation is described with a set of parameters describing the operation of either the IMT 5G N71 system or the DTTB system. They are derived from ITU recommendations and depend on the type of environment where a system is deployed.

The parameters are listed in Tables 1, 2 and 3 [12], [17], [18]. The choice for the propagation model has been based on the recommendations of the ITU. Model ''ITU-R P.1812'' is found to be the most recommended model in the considered case studies. Table 3 shows the weather parameters used to implement this propagation model based on average weather conditions in KSA. In addition, the selected map resolution is presented. The selection of the map resolution is a trade-off between the required simulation time and the resolution of the final results. In both parts of this investigation study, the highest possible resolution with feasible simulation time was chosen while making sure that increasing the resolution further does not change the final outcome or study conclusion. As part of the propagation model, time and location variability are defined. Time variability is the percentage of time that the predicted signal is exceeded during an average year [19]. On the other hand, the location variability is the percentage of locations within, say, an area with 100 to 200 m sides that the predicted signal is exceeded [19]. Both the time percentage and location probability are used initially at the default values selected by the simulation software, i.e., at 50%. When simulating the links with highest interference impact, such as the impact on

TABLE 1. DTTB system parameters.

Parameter	Rural	Urban
Tx Antenna Pattern	Omni-directional	
Tx Height (m)	300	150
Tx Transmit Power (dBm)	67	67
Channel bandwidth (MHz)	8	8
Rx Noise Figure (dB)	7	7
Rx Antenna height (m)	10	10
Rx Antenna Pattern	ITU-R BT.419-3	
Rx Antenna Gain (dBi)	9.15	9.15
Rx Noise floor (dBm)	−97	−97
Protection ratio $\frac{C}{N+I}$ (dB)	21	21

TABLE 2. IMT system parameters.

Parameter	Rural	Urban
Cell radius (km)	8	5
No. of Sectors	3	3
BS antenna down-tilt (°)	3	3
BS antenna pattern	ITU-R F.1336 rec3	
BS antenna Gain (dBi)	15	15
Bandwidth-Part I (MHz)	10	10
Bandwidth-Part II (MHz)	35	35
UL protection $\frac{I}{N}$ (dB)	−6	−6
DL protection $\frac{C}{I+N}$ (dB)	9.5	9.5
UE height (m)	1.5	1.5

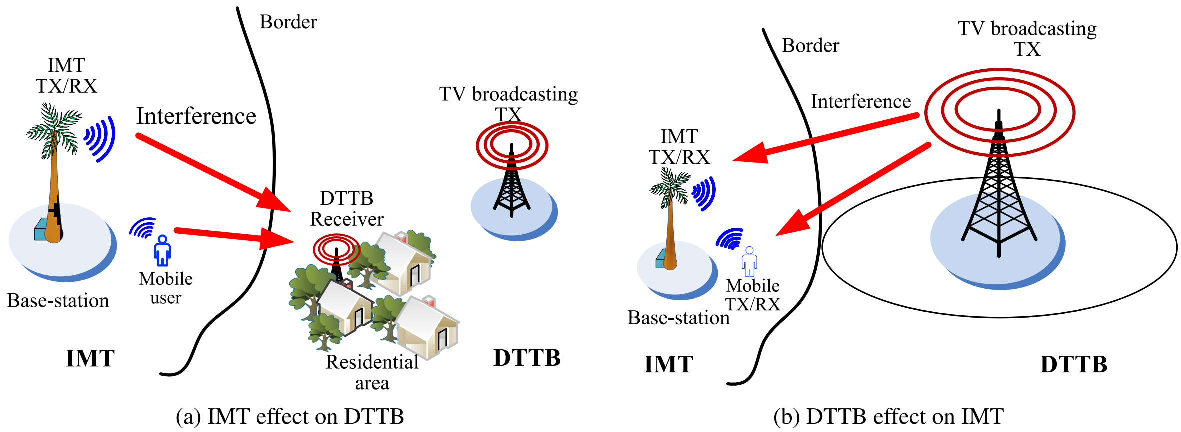

FIGURE 1. (a) Interference from IMT system into DTTB receiver (b) Interference from DTTB system into IMT service.

TABLE 3. Propagation model parameters.

Parameter	Selected value
Propagation Model	ITU-R P. 1812
Temperature (° C)	35
Water Level (gm/m^3)	0.32
Air pressure (hPa)	1013
Map Resolution(m×m)	200 × 200

IMT UL, additional time variabilities are simulated at 10% and 5%. However,we consider only 50% location for both the wanted signal (IMT signal) and the unwanted signal (DTTB signal) since it has less impact on the results.

B. METHODOLOGY OF ANALYSIS

In this investigation, two metrics are considered: the carrier-to-interference-plus noise $C/(I + N)$ and interference-to-noise (I/N) ratios. The $C/(I + N)$ is considered for the Down-Link (DL) connections while the I/N is considered for the IMT UL connection. These metrics account for the ability of the receivers to overcome the impact of received interference power if it is below a certain threshold. Using $C/(I + N)$ as a protection threshold leads to a more realistic and relaxed result when simulating interference impact. On the other hand, selecting the interference-to-noise ratio I/N results in a more conservative estimate of the interference impact since the interference power is compared to the noise floor power level without considering the received carrier power, which results in a much more stringent requirement. As a result, utilizing $C/(I+N)$ is more suitable when the carrier is more predictable, which is the case when analyzing the impact on IMT DL connections and DTTB receivers.

On the other hand, since IMT BSs are designed to have a lower sensitivity threshold compared with IMT UEs, and because their antenna has a significantly higher height than IMT UEs, it is expected that IMT UL is more susceptible to interference than DL. In addition, when the IMT BS is impacted by interference, therefore, all UEs connected to it will subsequently be impacted too. Moreover, the variable location of the transmitter in this case, i.e., the UE, makes predicting and simulating the received carrier power less accurate. As a result, the more conservative threshold metric I/N is used to assess the effect of the DTTB transmitters on the UL of the IMT system.

When simulating the impact of IMT network on the DTTB system, the number of base-stations used is set to 19 for the IMT and one for the DTTB systems [12]. Both IMT and DTTB transmitters are set to operate at the same frequency when simulating co-channel interference. However, for adjacent-channel interference analysis, the IMT BS carrier frequency is assigned the first adjacent-channel frequency below that of the DTTB Tx. This is facilitated by using an IMT BW of only 10 MHz, as shown in Table 2, which is sufficient and well represents a source of interference in Part I of this study. Moreover, the impact of IMT UEs on DTTB receivers is analyzed, where the locations of the UEs is distributed randomly inside the coverage area of each IMT BS cell. We simulate multiple locations in the coverage area of each IMT BS by considering around ten subscribers actively connected to each BS. Since the IMT UEs are expected to have less impact compared with IMT base-stations, only the worst-case co-channel interference is considered when simulating their impact on the DTTB system. Additionally, Monte Carlo interference simulations are preformed to estimate the probability of having $C/(I+N)$ greater than the required protection ratio. The simulation is done assuming IMT base-stations have all sectors turned-on with 200 random location samples for each statistical simulation run distributed uniformly inside the coverage area of the DTTB transmitter.

Note that the value of the simulated received signal strength depends on the selected propagation model. ITU clutter and terrain-aware propagation models for the UHF band are used

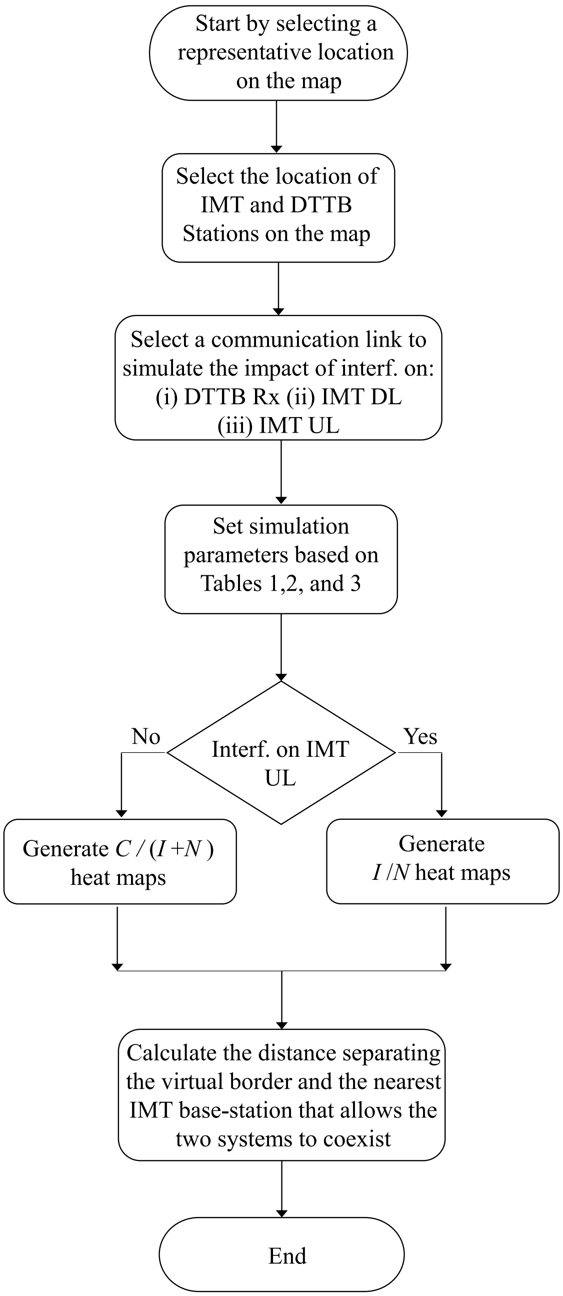

FIGURE 2. Flow chart for calculating the required separation distance.

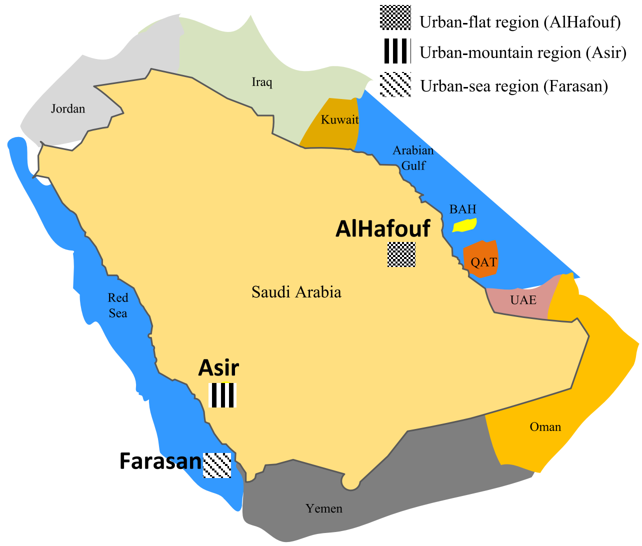

FIGURE 3. Selected locations in KSA.

to enhance the simulation's representation of the real-world environment. As opposed to the commonly used empirical models [20], [21] which provide a generic estimation of the value of protection criteria between the two networks, terrain-aware models provide a more realistic result.

For each selected area, the simulation software produces coverage heat maps for all potential locations of the receivers. The maps show the value of I/N or $C/(I+N)$, where I and C are the power of IMT interference and that of TV carrier, respectively, when considering the impact of IMT system on the DTTB receivers. For the impact on the IMT system, I represents the interfering power of DTTB transmitter. A certain point on the map is considered protected if I/N is smaller or $C/(I+N)$ is larger than a required threshold given in Tables 1 and 2. The receiver is configured to have a filter response to reject adjacent channels. The receiver filter rejection ratio, for the first adjacent channel, is set to 20 dB [22]. Figure 2 summarizes the simulation process for calculating the required separation distance in each scenario.

C. CHOICE OF LOCATIONS

In this study, three different geographical locations inside the KSA were selected to represent variety of terrains: (i) urban-mountains (Asir) with a map size of 120 km × 60 km, (ii) urban-sea (Farasan Island and Jazan) with a map size of 85 km × 75 km, and (iii) urban-flat (AlHafouf) with a map size of 130 km × 90 km when simulating the impact of IMT on the DTTB network, and with a larger map size 330 km × 160 km when simulating the impact of DTTB on the IMT network because it extends for much farther distances in a flat terrain. These locations are shown on the map in Figure 3.

III. EFFECT OF IMT SYSTEM ON DTTB SERVICE

A. URBAN MOUNTAIN TERRAIN: ASIR

The first location to be presented in this paper is an urban mountain terrain in Asir. The system parameters and variables used throughout this section are based on what was presented in Subsection II-A.

1) COEXISTENCE WITH SELECTED SECTORS OF BASE-STATIONS TURNED-OFF

Normally, IMT base-stations utilize multiple sectors to serve users located at all directions. However, when a specific sector is serving an area that is outside the IMT network desired area of coverage, i.e., at the edge of the border of the network, the sector can be selectively turned-off to minimize

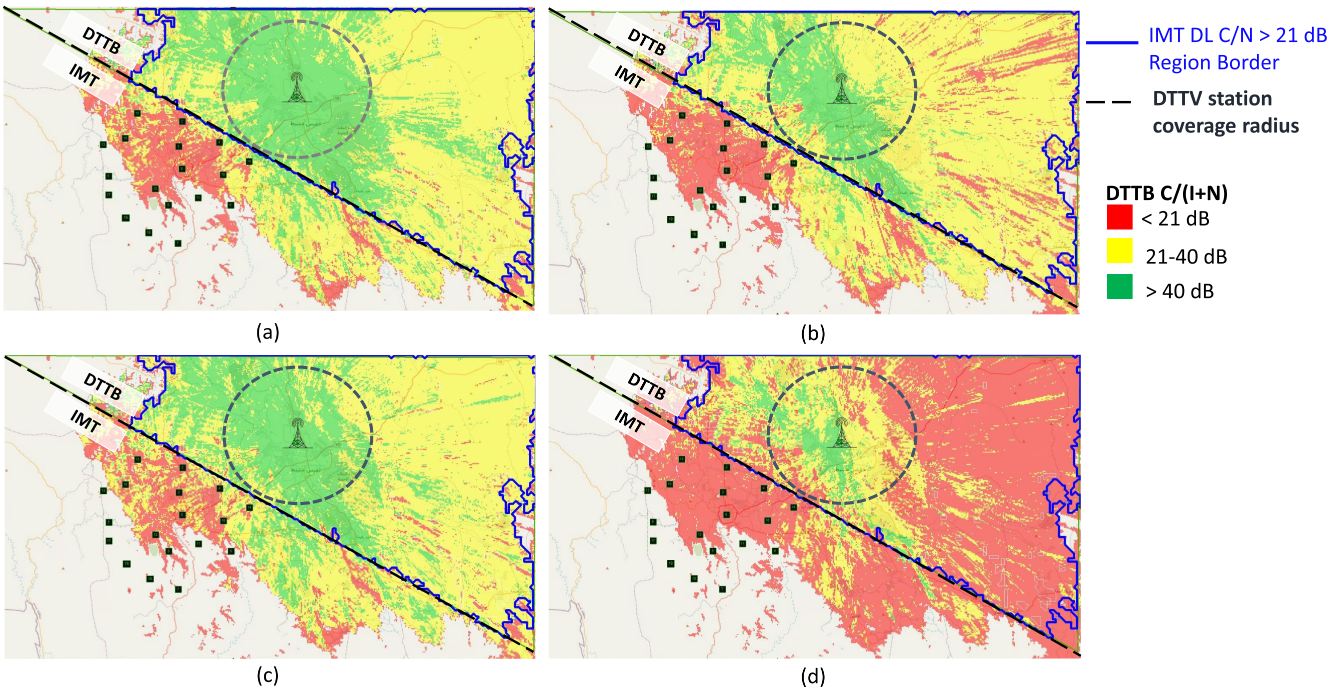

FIGURE 4. $C/(I+N)$ heat map in Asir with sectors transmitting toward the DTTB network at the edge of border are turned-off: (a) Adjacent Channel and (b) Co-channel Interference. And, $C/(I+N)$ heat map with all sectors are turned-on: (c) Adjacent Channel and (d) Co-channel Interference.

the interference beyond the network borders. Figure 4a shows the adjacent channel $C/(I+N)$ heat map when the closest IMT base-station is on the edge of the DTTB network coverage circle. Similarly, the co-channel $C/(I+N)$ heat map is shown in Figure 4b. In both cases, the interference induced by the IMT network didn't cause the $C/(I+N)$ value to become below the required protection ratio (21dB) in more than %95 of the locations inside the coverage area of the DTTB network. As a result, the two networks can coexist when selected IMT sectors transmitting toward the DTTB network at the edge of border are turned-off.

2) COEXISTENCE WITH ALL SECTORS OF IMT BASE-STATIONS ON

When all sectors are used in the IMT stations near the edge of the border, the IMT coverage could spillover to DTTB coverage area. As Figure 4c demonstrates, this wouldn't be an issue when considering adjacent channels interference, as large parts of the DTTB coverage will experience $C/(I+N) > 40$dB, which is much more than the required protection ratio. If this restriction is not implemented in the IMT network, the interference will result in significant areas with $C/(I+N)$ below the required protection ratio, as shown in Figure 4d. To overcome this interference impact, simulations have been carried out, which showed that IMT base-stations, sharing the same frequencies with DTTB tower and with all of their sectors turned-on, are required to have a separation distance of 8 km between virtual border and the nearest allowed IMT BS.

In addition to turning-off the sectors transmitting toward the DTTB network near the border, other mitigation techniques were simulated to examine their impact on the exclusion zone. These techniques included: (i) varying the IMT base-stations antenna down-tilting from $-3°$ to $-10°$, (ii) adjusting the IMT base-station output power from 43 to 46 dBm, and (iii) changing the IMT tower height from 20 to 30 m, and the DTTB tower height from 150 to 300 m. In summary, these simulations showed that those techniques, when used without controlling the IMT sectors, had minimal impact on the separation distance associated with it. Table 4 summarizes the required separation distance for all the simulation parameters.

3) STATISTICAL MONTE CARLO SIMULATION RESULTS

Since co-channel interference is the limiting element in determining the exclusion zone, as discussed in Section III-A2, a Monte Carlo interference simulation is preformed for the probability of having $C/(I+N)$ greater than the required protection ratio. Assuming IMT base-stations are still located up to the edge of the border with all sectors turned-on, the cumulative distribution function (CDF) is presented in Figure 5. The probability of having $C/(I+N) > 21$ dB is more than %95 for adjacent channels interference. On the other hand, this probability drops to %83 for co-channel interference which confirms the result presented in Section III-A2, which states that a 8km separation distance is required when all sectors are turned-on. Note that because the Monte Carlo simulation is based on distributing all DTTB

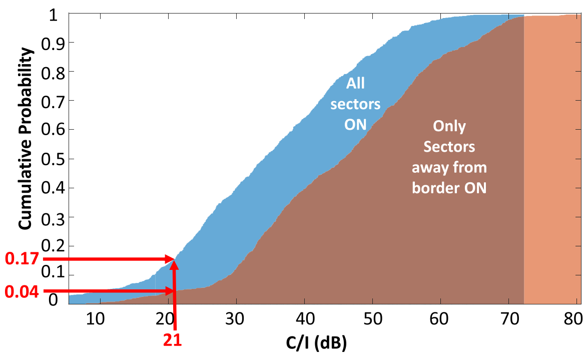

FIGURE 5. Monte Carlo simulation for Asir.

TABLE 4. Summary of required separation distance for Urban-Mountain: Asir.

Adjusted System Variable	Sep. Distance (km)
Co-channel & all sectors on	8
Adjacent channel & all sectors on	1
Co-channel & selected sectors turned-off	< 1
Adjacent channel & selected sectors turned-off	< 1

receivers within the tower coverage radius, the received carrier power C is much higher than the sensitivity level. Therefore, given the required protection ratio of 21 dB, I is expected to be much larger than N. Hence, we can assume $C/(I+N) \approx C/I$ which is used by the the software on all Monte Carlo results.

4) COEXISTENCE WITH IMT UE

The impact of the IMT base-stations on a DTTB receiver was presented in detail in the previous sections. The other component of the IMT network is the UE. Because of its lower output power, shorter antenna height and being idle most of the time, it is expected that its impact is significantly less than that of the base-stations. Figure 6 shows the $C/(I+N)$ heat map when UEs are considered. The results demonstrate that the interference caused by UEs is minimal and restricted to a radius of less than 1 km, even when UEs are simulated with their maximum output power (23 dBm) as co-channel interferer. Therefore, it can be concluded that the IMT base-stations are the main factor which defines the exclusion zone for the IMT network.

B. URBAN SEA TERRAIN: FARASAN ISLAND AND JAZAN

The second location considered in this study is the urban sea terrain in the Farasan island and Jazan area. This area is characterized by sea terrain which separates Farasan island and Jazan city by ~ 42 km. This geographic distance plays a major role in reducing the interference effect from the IMT base station and UE on the DTTB receivers, as will be shown in the next subsections.

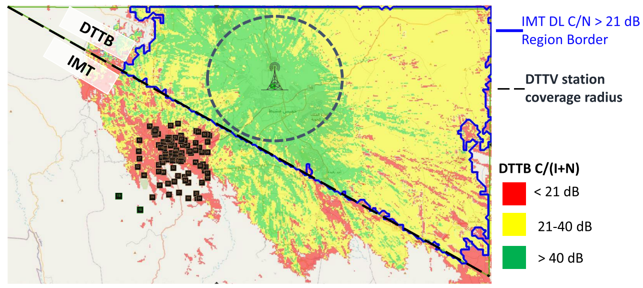

FIGURE 6. $C/(I+N)$ heat map in Asir for IMT UEs.

1) COEXISTENCE WITH SELECTED SECTORS OF BASE-STATIONS TURNED-OFF

Figure 7a and Figure 7b show the adjacent and co-channel $C/(I+N)$ heat map when the sectors transmitting toward the DTTB network at the edge of border are turned-off. In both cases, the cumulative interference induced by the IMT base-stations on the DTTB network results in a $C/(I+N)$ value above the DTTB receiver protection ratio of 21 dB in all the DTTB network coverage area. Hence, the two primary systems can coexist, taking into consideration only the effect of IMT on DTTB.

2) COEXISTENCE WITH ALL SECTORS OF IMT BASE-STATIONS ON

Similarly, in this location, we studied the cumulative interference of IMT base-stations on the DTTB receiver, with all antenna sectors radiating. Figure 7c and figure 7d show the $C/(I+N)$ heat map for adjacent and co-channel cases, respectively. It can be noticed that the cumulative interference effect increases in comparison with the case where some sectors are off, however, the measured $C/(I+N)$ is still above the required protection ratio in all the DTTB network coverage area. As a result, the IMT network can coexist with the DTTB system with all IMT sectors on.

3) STATISTICAL MONTE CARLO INTERFERENCE ANALYSIS RESULTS

As we did in the first location study, a Monte Carlo statistical interference simulation was performed for the sea terrain case. Figure 8 shows the CDF of C/I measure parameter for two cases when: (i) all IMT sectors are on, and (ii) only sectors away from the border are on. It can be noticed that the probability of having $C/I > 21$ dB is more than $\sim$ 99% for both co-channel interference cases. This implies the feasibility of the coexistence between the IMT and DTTB systems.

4) COEXISTENCE WITH IMT UE

In this section, we consider the IMT UE as the main interferer to the DTTB system. Figure 9 shows the $C/(I+N)$ heat map when UE was considered as co-channel interferer. It is worth noting that the UE is distributed based on

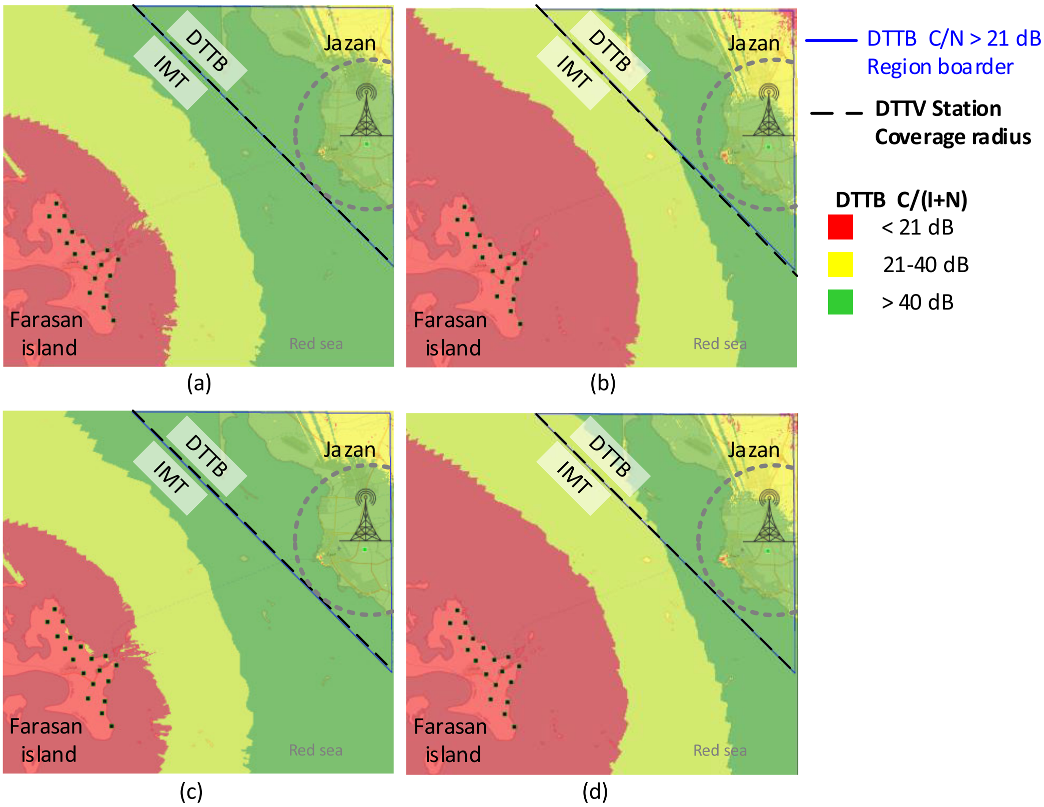

FIGURE 7. $C/(I+N)$ **heat map for Farasan island and jazan with sectors transmitting toward the DTTB network at the edge of border are turned-off: (a) Adjacent channel and (b) Co-channel interference. And,** $C/(I+N)$ **heat map with all sectors are turned-on: (c) Adjacent channel and (d) Co-channel interference.**

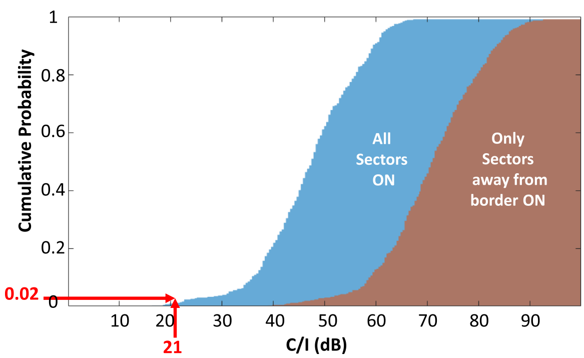

FIGURE 8. **Monte Carlo simulation for Farasan Island and Jazan.**

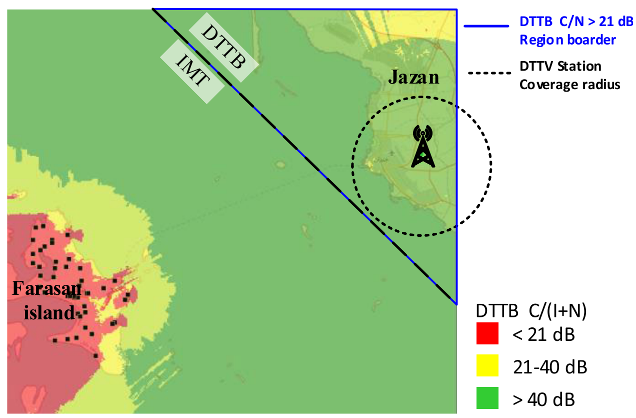

FIGURE 9. $C/(I+N)$ **heat map of IMT UE for Farasan Island and Jazan.**

the terrain of Farasan island. It can be noticed that the cumulative interference from UE is negligible due to the typical low nominal power and height of the UE, and the geographical distance between the two primary systems.

C. URBAN FLAT TERRAIN: AlHafouf

The third location is the rural terrain near AlHafouf and the urban terrain of AlHafouf city area, This area is categorized by Urban flat terrain which separates the rural area about 35 km away in the east to the urban area of AlHafouf city. The DTTB system is located in the rural area and the IMT network is in urban part of the AlHafouf city. The interference is caused due to the base stations of the IMT network and the UEs on the DTTB receiver. The parameters and variables of the DTTB and IMT systems are selected as mentioned in Tables 1, 2, and 3, respectively.

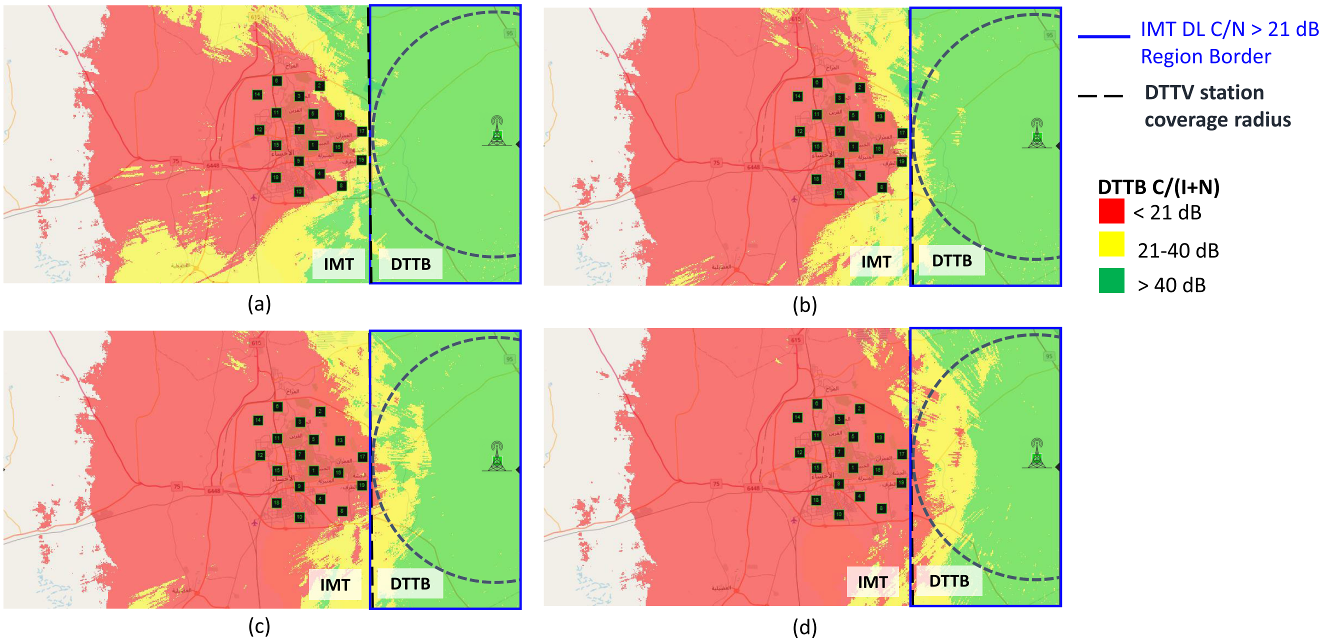

FIGURE 10. $C/(I+N)$ heat map in AlHafouf with sectors transmitting toward the DTTB network at the edge of border are turned-off: (a) Adjacent channel and (b) Co-channel interference. And, $C/(I+N)$ heat map with all sectors are turned-on: (c) Adjacent channel and (d) Co-channel interference.

1) COEXISTENCE WITH SELECTED SECTORS OF BASE-STATIONS TURNED-OFF

The heat maps for the adjacent channel and co-channel interference are shown in Figure 10a and Figure 10b, respectively, when all the sectors transmitting toward the DTTB network at the edge of border of the closest base-stations in the AlHafouf city are turned-off.

In both cases, the cumulative interference induced by the IMT base-stations on the DTTB coverage results in a $C/(I+N)$ value above the DTTB receiver protection ratio of 21 dB. Hence, the two primary systems can coexist, taking into consideration only the effect of IMT on DTTB.

2) COEXISTENCE WITH SELECTED SECTORS OF BASE-STATIONS TURNED-ON

The heat maps of $C/(I+N)$ for the adjacent channel and co-channel interference are shown in Figure 10c and Fig 10d, respectively, when all the sectors are on.

The desired protection ratio of 21 dB criteria is fulfilled by keeping the base stations 5 km and 10 km away from the virtual border in both cases of adjacent channel and co-channel interference, respectively. The separation distance in both cases are mentioned in the Table 5. With this adjustment of the distance, both IMT and DTTB systems can coexist without problem.

3) STATISTICAL MONTE CARLO ANALYSIS

The Monte Carlo simulation was performed for the adjacent channel and co-channel cases. The cumulative distribution function of the value of $C/(I+N)$ was computed, as shown in Figure 11. It is observed that the probability of having $C(I+N)$ greater than 21 dB is more than 95% of the locations in case of the adjacent channel interference. These observations strongly supports the idea that the IMT network can safely be deployed without affecting the TV broadcasting services across the virtual border. However, this probability

TABLE 5. Summary of required separation distance for Urban-Flat: AlHafouf.

Adjusted System Variable	Sep. Distance (km)
Co-channel & all sectors on	10
Adjacent channel & all sectors on	5
Co-channel & selected sectors turned-off	< 1
Adjacent channel & selected sectors turned-off	< 1

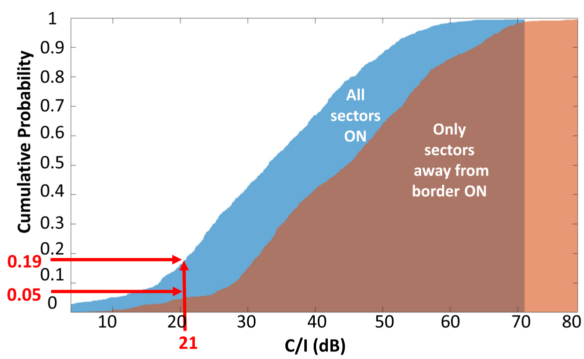

FIGURE 11. Monte Carlo simulation for AlHafouf.

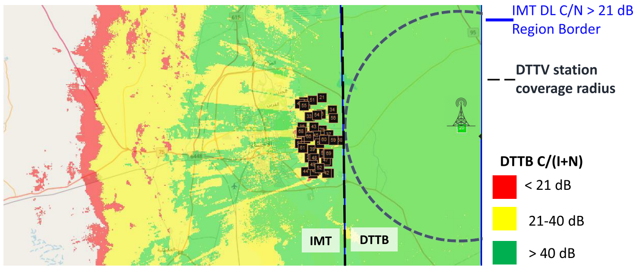

FIGURE 12. ***C*/(*I* + *N*) heat map of IMT UE for AlHafouf.**

drops to %81 for co-channel interference which confirms the result presented earlier that a 10 km separation distance is required when all sectors are turned-on.

4) COEXISTENCE WITH IMT UE

Similar to the prior regions, a heat map of $C/(I+N)$ is generated and depicted in Figure 12. It is observed that IMT UEs cause no impactful interference due to their low power emission and smaller area of coverage even when they act as co-channel interferers.

IV. EFFECT OF DTTB SYSTEM ON IMT SERVICE

A. URBAN MOUNTAIN TERRAIN: ASIR

Similar to the previous section, the first location to be presented in this section is an urban mountain terrain in Asir.

1) DTTB INTERFERENCE IMPACT ON IMT UP-LINK

As explained previously, IMT base-stations utilize multiple sectors to serve users located at all directions. However, to minimize the interference impact, switching-off the sectors of IMT transmitters pointing toward the DTTB network near the border is considered. Since only sectors directed away from the IMT coverage area in base-stations near the border are considered, the impact on IMT subscribers is minimized.

Assuming time variability of %50, Figure 13a shows the I/N heat map when all sectors are used in the IMT stations near the edge of the network border. Similarly, Figure 13b shows I/N heat map when certain sectors, which are directed toward the DTTB network, are turned-off. The interference induced by the DTTB network can be alleviated by utilizing a separation distance from the network border to the nearest permissible location for IMT BS deployment where the I/N value to become above the required protection ratio (-6 dB) in all locations inside the coverage area of the IMT network. By turning-off the sectors directed toward the DTTB network, the required separation distance is reduced from 35 km to 20 km.

Moreover, when the time variability is reduced to %10, turning-off certain sectors becomes more necessary. The results indicate that when certain sectors are turned-off, the required separation decreases to 21km from 39km. Moreover, when the time variability is reduced further to %5, turning-off certain sectors does improve the interference impact on the separation distance from 40km to 23km.

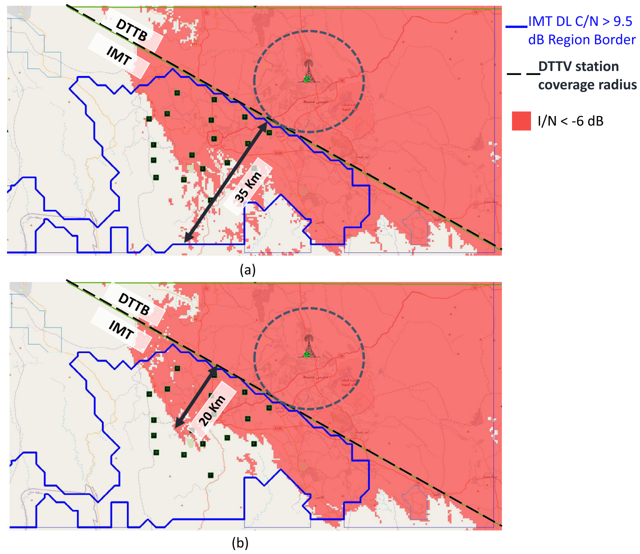

FIGURE 13. ***I*/*N* heat map in urban mountains terrain (Asir) assuming %50 time variability with: (a) all sectors are turned-on, (b) sectors receiving from DTTB network side are turned-off.**

2) DTTB INTERFERENCE IMPACT ON IMT DOWN-LINK

When considering the down-link of the IMT network, all the land areas covered by the IMT network will experience $C/(I+N) > 9.5$ dB, which is the required threshold to protect the IMT network. This is expected as explained in Section II-B since the down-link connection is less susceptible to interference due the lower receiver antenna height and has worse receiver sensitivity (UE).

3) MITIGATION TECHNIQUES TO MINIMIZE DTTB INTERFERENCE IMPACT

In addition to turning-off the sectors receiving from the DTTB network near the network border, other mitigation techniques were simulated to examine their impact on the interference level. These techniques included: (i) varying the IMT base-stations antenna down-tilting from $-3°$ to $-10°$, (ii) adjusting the IMT base-station output power from 43 to 46dBm, and (iii) changing the IMT tower height from 20 to 30m. In summary, these simulations show that those techniques, when used without controlling the IMT sectors, had minimal improvement on the received interference level in the impacted regions.

Since the UL interference represents the bottleneck when minimizing the interference impact, the scenario of reallocating the TV tower transmitting in the n71 up-link band (663 - 698 MHz) is simulated. Assuming the worst case time variability of %5, the distance from the network border where the interference is above the protection ratio is reduced. In summary, combining both techniques of (i) turning-off the sectors receiving from the DTTB network near the network border and (ii) reallocating TV transmitters away from n71 UL frequencies to the mid-frequency in the n71 DL band (634.5 MHz), will give the optimum minimal impact on

TABLE 6. Separation distance in km from the network border (urban mountains) to the nearest permissible location for IMT BS deployment.

Time Variability	All sectors on	Sectors toward DTTB off
50%	35	20
10%	39	21
5%	40	23
5% (with freq. reallocation)	32	22

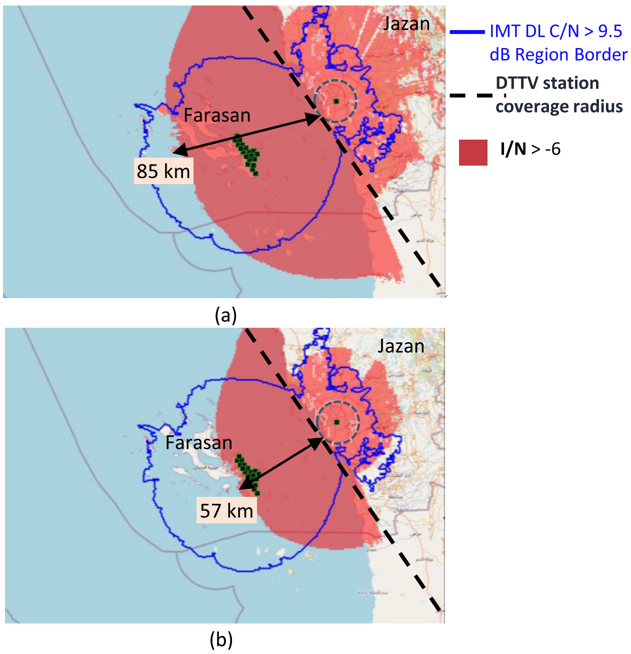

FIGURE 14. ***I*/*N* heat map in urban sea terrain: Farasan island and Jazan assuming %50-time variability with: (a) all sectors are turned-on, (b) sectors receiving from DTTB network side are turned-off.**

the IMT network. However, especially when the %5 time variability is assumed, some areas near the network border will still not meet the required I/N protection ratio, which can be alleviated by establishing a separation distances to protect the IMT network. Table 6 summarizes the required separation distance between the network border and its nearest allowed location for IMT BS to operate free from UL interference.

B. URBAN SEA TERRAIN: FARASAN ISLAND AND JAZAN

As mentioned in the previous section, Farasan island and Jazan area is an urban sea terrain where the two primary systems are separated by ~ 42 km (i.e., DTTB and IMT) of sea terrain. In the following, we show the interference from the DTTB system on the IMT up-link and down-link using the I/N and $C/(I+N)$ criteria, respectively.

1) DTTB INTERFERENCE IMPACT ON IMT UP-LINK

For a time variability of 50%, Figure 14a and Figure 14b show the I/N heat map when all IMT sectors were turned on and when the sectors toward the interferer system (DTTB) were

TABLE 7. Separation distance in km for urban sea terrain: Farsan island and Jazan to the nearest permissible location for IMT BS deployment.

Time Variability	All sectors on	Sectors toward DTTB off
50%	85	57
10%	333	140
5%	409	204
5% (with freq. reallocation)	–	–

turned off, respectively. Owing to the effect of sea terrain, the interference from the DTTB network cause the I/N values to exceed the protection ratio (−6 dB) for a distance of 85 km toward the victim system (IMT). This interference distance can be reduced to 57 km by turning off the IMT sectors toward the DTTB network, as shown in Figure 14b.

Moreover, when the time variability is reduced to 10 and 5%, the DTTB interference distance increases to 333 and 409 km, respectively. Similarly, it can be noted that turning off the IMT sectors toward the DTTB network can reduce the interference distances to 140 km for time variability of 10% and 204 km for time variability of 5%.

2) DTTB INTERFERENCE IMPACT ON IMT DOWN-LINK

The IMT down-link is less sensitive to DTTB interference owing to the $C/(I+N)$ criteria. The simulated $C/(I+N)$ using the same map area shows that the IMT network is protected with $C/(I+N)$ ratio $>$ 9.5 dB in the IMT coverage area.

3) MITIGATION TECHNIQUES TO MINIMIZE DTTB INTERFERENCE IMPACT

As discussed in the previous sections, the up-link interference represents the critical interference from the DTTB network. Here, we study the impact of frequency reallocation of the TV station transmitting on the n71 frequency band (663 to 698 MHz). The I/N values for worst-case 5% time with TV frequency reallocation were simulated. The results show a reduction in the DTTB interference even when all IMT sectors are turned on. Note that the interference is reduced further when the IMT sectors toward the DTTB were turned off. Table 7 summarizesthe required separation distances between the border and the nearest permissible location for an IMT base-station deployment, for 50, 10, and 5% time. Also, this table shows the separation distance after considering TV frequency reallocation.

C. URBAN FLAT TERRAIN: AlHafouf

The third location is presented as urban flat terrain in AlHafouf area. The system parameters and variables used for this location similar to what is used in the previous sections.

1) DTTB INTERFERENCE IMPACT ON IMT UP-LINK

Like the previous areas, three values of time variability are considered: 50%, 10% and 5% to study the impact on the up-link interference. A heat map I/N for 50% time variability when all the sectors are turned on is shown in Figure 15a.

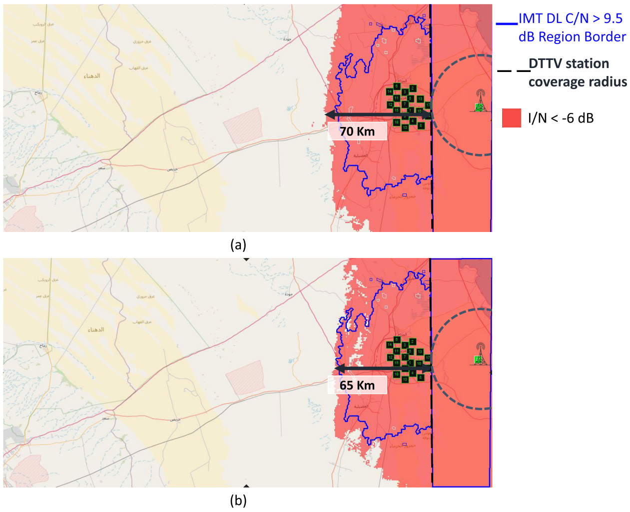

FIGURE 15. ***I/N* heat map in urban flat terrain: AlHafouf assuming %50-time variability with: (a) all sectors are turned-on, (b) sectors receiving from DTTB network side are turned-off.**

TABLE 8. Separation distance in km from the network border for urban flat terrain: AlHafouf to the nearest permissible location for IMT BS deployment.

Time Variability	All sectors on	Sectors toward DTTB off
50%	70	65
10%	140	100
5%	255	135
5% (with freq. reallocation)	110	65

Further, the heat map for 50% time variability when all the sectors receiving from the DTTB system kept off is shown in Figure 15b.

It is noted that using a separation distance between the IMT network and the virtual border of around 70 km will result in avoiding the up-link interference impact and fulfilling the set protection ratio criteria. The separation distance reduces to about 65 km when the sectors facing the DTTB system are turned off.

2) DTTB INTERFERENCE IMPACT ON IMT DOWN-LINK

In case of the down-link of the IMT network, the value of $C/(I+N)$ does not fall below 9.5 dB which is desired threshold for avoiding the interference of the IMT network. As mentioned earlier too that the down-link are less vulnerable to interference due to low antenna height and less receiver sensitivity.

3) MITIGATION TECHNIQUES TO MINIMIZE DTTB INTERFERENCE IMPACT

In order to mitigate the interference impact and reduce the required separation distance, the frequency of the TV station transmitting on the n71 is reallocated to the center of the DL band. The simulation result, which is done at the wort-case time variability of 5%, shows that the separation distance can be reduced by a factor of half when the TV tower frequency is reallocated. The separation distance in case of up-link interference is summarized in Table 8 for time variability of 50%, 10%, and 5%, respectively.

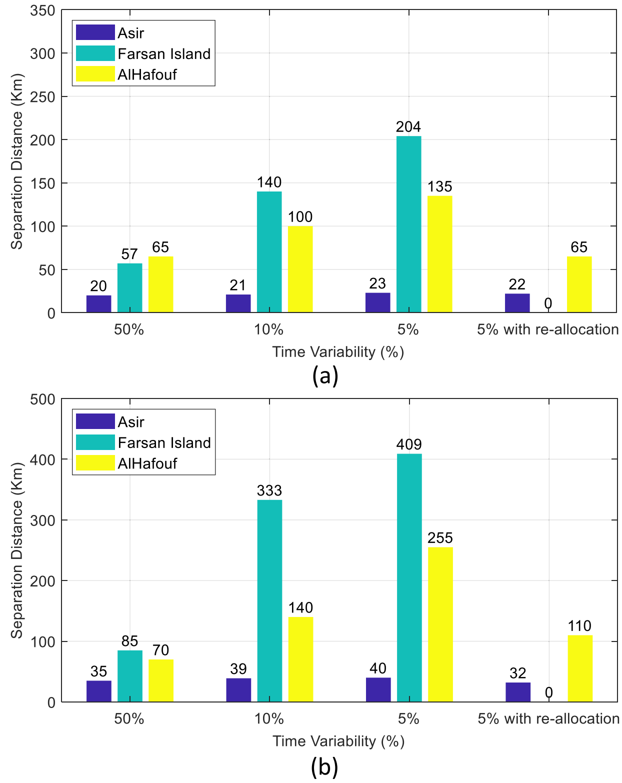

FIGURE 16. Separation distance summary: (a) sectors receiving from DTTB network side are turned-on, (b) all sectors turned-on.

TABLE 9. Separation distance presented in previous works.

Reference	Separation Distance (km)	Notes
[13]	160	700 MHz, measured mixed signal path
[13]	260	700 MHz, measured warm sea path
[12]	192	600 MHz, 10% time var. generic simulation
[23]	278	700 MHz, 5% time var. generic simulation

Figure 16 summarizes all the separation distances presented in this section. The results show that the worst-case separation distance is in the sea terrain, while the lowest is in the mountain terrain. The ratio between the highest and lowest required separation distance can be as high as 10 times.

Since the IMT up-link is the most sensitive link to interference, the results from this study are compared with prior works in Table 9. These previous results were either measured signal strength experiments or generic simulations without taking into account the type of terrain. This study, however, presents a more comprehensive results showing that, for instance, a mountain terrain doesn't require a large separation distance. When sea borders are considered, the prior results become closer to the low time variability outcomes presented in this study.

V. CONCLUSION

This paper studied the coexistence between DTTB and IMT networks in the sub-700 MHz using advanced terrain-aware simulator. The results show that the coexistence is possible when the required separation distance is met between the two networks. The most critical communication link defining the required separation distance is the IMT up-link where the impact of the DTTB towers on the IMT BS is found to be more significant. The interference impact on the IMT UL can be mitigated when a specific separation distance is met depending on the environment. The required separation distance increases between 3-10 fold in sea and flat borders compared with border with mountains terrain, which emphasizes the importance of considering the type of terrain when studying spectrum sharing in the sub 700-MHz band. The separation naturally exists in some area such as in sea borders. This separation distance varies significantly depending on the type of terrain where the network is deployed. Note that the mountain terrain has the lowest required separation distance of less than 40 km, while it could be as high as 85 km in sea borders when all sectors are on and assuming 50% time variability. In order to reduce this separation distance, the most efficient interference mitigation technique is to reallocate the frequencies used by DTTB towers transmitting in the upper part of the n71 band near the border to the lower half of the band. The next effective technique is to turn off IMT BS sectors pointing toward DTTB network.

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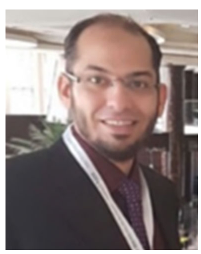

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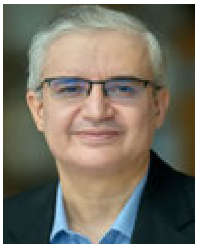

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