Coexistence for LTE-Advanced and FSS Services in the 3.5GHz Band in Colombia

German Castellanos*
dep. of Electronics Engineering.
Colombian School of Engineering.
Bogota, Colombia.
german.castellanos@escuelaing.edu.co

Guillermo Teuta*
dep. of Electronics Engineering.
Colombian School of Engineering.
Bogota, Colombia.
guillermo.teuta@escuelaing.edu.co

Hernan Paz Penagos*
dep. of Electronics Engineering.
Colombian School of Engineering.
Bogota, Colombia.
hernan.paz@escuelaing.edu.co

Wout Joseph+
dep. of Information Technology.
IMEC - Ghent University.
Ghent, Belgium.
wout.joseph@UGent.be

***Abstract*— The 3.5GHz band is an optimal candidate for 5G networks due to its propagation characteristics and massive bandwidth. However, services like the Fixed Satellite Service (FSS) are using this band in several countries. Therefore, this paper presents a coexistence study of the Long Term Evolution - Advanced (LTE-A) and FSS services in the 3500-3700 MHz in Colombia. Simulations were done in realistic scenarios in the city of Bogota, Colombia. Preliminary results show that critical scenarios are the ones from the LTE eNodeB (eNB) and Users Equipment (UE) nodes to the FSS earth stations. The study includes the analysis of Guard Bands (GB) and arrival angles into the Protection Distances (PD). Results show that the PD is highly dependent on the angle of the interfering signal and the GB used. The PD for a cochannel interference in a suburban scenario is higher than 250km, in the worst-case scenario, and could be reduced down to 17.5 km if a 25 MHz GB is included and the angular difference of the interfering LTE-A signal is 42°. Moreover, our results show that the PD needed for interference from UE are 100 times less compared to the eNB ones.

Keywords*— *LTE-Advanced, FSS, Interference, Coexistence, Protection distance, Guard band, 3.5GHz band.

I. Introduction

The National Spectrum Agency (ANE), as part of the Information, Communication and Technology Ministry (MinTIC) of Colombia, is investigating the availability of new bands for the deployment of 5G IMT services. Based on the results from the World Radio Conference (WRC) in 2007 and 2015, ANE is interested in starting the study of new bands at medium and higher frequencies for future use in IMT services [1]. One of the cases is the spectrum band between 3300MHz to 3700MHz to allocate an additional 400MHz to IMT services [2]. However, in this band, there are also Fixed Satellite Services (FSS), which must be protected against interference, ensuring the coexistence of both services in that band [3], [4]. No precise knowledge of the location of FSS receivers is present; hence all the control of them has to be done at the LTE transmission side. The International Telecommunication Union (ITU), in its Recommendation M-1036-6, defines new bands and allocation techniques for spectrum efficiency. Time Division Multiplexing (TDD) allows allocation flexibility and spectrum efficiency is the recommended operational mode for 5G deployments [5], [6]. Moreover, the 3rd Generation Partnership Project (3GPP) has specified three new bands for 5G, i.e., band 42, band 43 and band 48 for LTE-A services in the 3400-3800MHz Range[7].

* Members of the Ecitronica Research Group of Colombia (South America). This project was co-funded by the Colombian Spectrum Agency (ANE) with especial collaboration agreement #034 of 2019.
+ International adviser from WAVES-IMEC research Group in Belgium.

The coexistence studies aim to determine zones where the usage of LTE-A services will not interfere with FSS services. This interference is cataloged in no-interference, tolerable and harmful. Being the last one that compromises the performance of the victim system [8]. These zones could be determined by distances, called protection distance (PD), or by frequency, called guard bands (GB). In this paper, we investigate the methodology to determine these parameters in order to reduce the interference between LTE-A and FSS services in Colombian territory. The novelty of this paper resides in the evaluation of different guard bands and elevation angles to determine the protection distance in different scenarios in equatorial countries.

The outline of this paper is as follows. Section II presents a survey of the coexistence in the 3.5GHz band, including the spectrum regulations from the regulators around the world and the international studies of coexistence done. The methodology used to describe the scenario of interference between the LTE-A and FSS systems, the tool employed for the system assessment and the interference evaluation parameters are presented in Section III. Results for tolerable interference are discussed in Section IV, and Section V collects the conclusions and presents future work.

II. Coexistence in the 3.5GHz band

A. Spectrum for IMT services

As a result of the World Radio Conference (WRC) in 2007 and 2015, the 3300-3700 MHz band was identified and reserved at Colombia, according to national note CLM 46 of National Table of Attribution of Frequency Bands (CNABF) [9], to provide IMT services worldwide. The WRC of 2019 [10], confirms the identification of the band for several countries in Region 2 and determines (in the MOD 5.434) that administrations shall seek agreement with other administrations as well as with the previous operator in this band, respecting space satellite operation according to with the Radio Regulations. ITU in Recommendation ITU-R M.1036-5 provides guidelines on the selection of frequency arrangements applicable to the terrestrial component of IMT systems. These guidelines assist administrations in defining technical aspects related to the bands identified in the Radio Regulation (RR) [6].

Besides, the ITU recommends the channelization for the 3400-3600MHz band. For time division duplexing (TDD) systems, it is recommended the usage of whole 200MHz bandwidth (F1), while for FDD (F2), the downlink (DL) used 3510-3590MHz and 3410-3490MHz for the uplink (UL). Finally, in the WRC 19 the usage of TDD mode for the whole 3300-3700MHz band (F3), as shown in Fig. 1 was approved [6]. One of the advantages of using this band in TDD mode is the reduction of latencies to meet the requirements of 5G. In 3GPP, these frequencies have been defined as bands 42 (3400-3600 MHz), 43 (3600-3800 MHz) and 48 (3550-3500 MHz) of Table 5.5-1 of ETSI TS 136 101 V14.5.0, as well as n78 (3300-3800 MHz) of the 5G radio bands specified in 3GPP TS 38.101 -1 of Release 15 of LTE [7]. Moreover, in Recommendation ITU-R M.1012 presents the definition of functions for IMT-A systems. These are used to define the evaluation scenarios [11], while the characteristics of terrestrial IMT-A systems for frequency sharing and interference analysis are presented in ITU-R Report M.2292-0 [12].

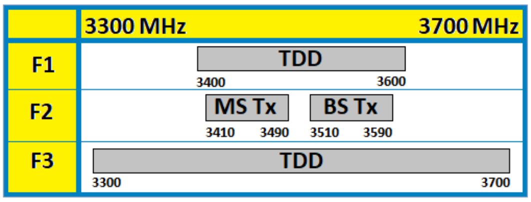

Fig. 1. Channel arrangements for C-Band in ITU-R M.1036-6 [6].

B. Regulatory Aspects

The ITU has developed several recommendations and reports related to the use and operation of IMT services in the FSS bands. They seek to protect the FSS receiving earth stations through a protection distance from the mobile terrestrial stations. The protection distance (PD) is defined as the distance an interfering node should be placed from the victim node, in order to not interfere the victim node with harmful or tolerable interference, depending on the regulation associated. The Report ITU-R M.2109 [13], presents coexistence studies between IMT-A systems and geostationary-satellite networks in the fixed-satellite service in the frequency bands 3400-4200 and 4500-4800 MHz. It stipulates that the separation distances are dependent on the deployment of both technologies and varies according to the methodologies used. However, the report specifies that coexistence is only possible outside the delimited zone by the minimum protection distance. This distance is specified by the administrations consequently to the required interference level. Moreover, it recommends licensed FSS and IMT deployments to overlook potential interferences. The Report ITU-R S.2150 [14] introduces the usage of adaptive antennas pointed to the interference source to measure the interference signals and subtract them digitally from the desired signal reducing the overall interference, compared in particular with shielding techniques. The Report ITU-R S.2199 [15], describes the protection margins for the interference from Broadband Wireless Access networks (BWA) into the FSS services. In concludes that for co-channel sharing, a protection distance from several tens to 100 km must be implemented; for out-of-band emissions, only a few km; and for FSS receiver saturation: from a few to several km.

The Report ITU-R S.2368 [16], introduces the sharing studies between IMT-A systems and geostationary-satellite networks in the FSS in the frequency the 3400-4200 and 4500-4800 MHz bands. For in-band emission, the protection distances should be higher than 100 km and could extend up to 525 km. Therefore, this arrangement is not recommended. For immediate adjacent band emissions, i.e. 0 MHz guard band, accounting for the long-term interference criterion, the required protection distance could be from 5 km to tens of km for IMT-A macrocells. For small the PD ranges from 900 m to less than 5 km in outdoor deployments. The protection between the LTE-A eNB and an FSS earth station can be reduced by using a guard band greater than 0 MHz.

Moreover, the usage of RF filters in the FSS receptor provides no significant reduction in protection distances. Finally, the coexistence between IMT-A and FSS is feasible only when FSS stations are in specific and known locations, and IMT-A deployment is limited to areas outside the minimum separation distances to protect those FSS stations. In this case, administrations should determine separation distances by defining the FSS protection criteria.

In Colombia, the Resolution 181 from 2019, determines that bands between 1427 to 1518 MHz, 1755 to 1780 MHz, 2155 to 2180 MHz and 3300 to 3700 MHz are reserved for the future IMT operations [17] Similarly, MinTIC establishes that FSS stations must take into account provisions of Article 9 and Appendix 5 of the ITU RR [8]. Also, in the annotation CLM 98 of the national table of frequency allocation (CNABF), it is established that all frequency bands above 1 GHz that share primary allocation between terrestrial and space services must comply with the article 21 of the ITU RR [8], [9].

C. Coexistence Studies

Several countries around the world have done coexistence studies between IMT services and FSS in the 3.5GHz band. In the United States of America (USA), the Report ITU-R S.2368 analyses the potential interference made by IMT services to the DL of FSS services in the 3.4-4.2GHz band. Cases were evaluated both within the band and for an adjacent band, including the short and long-term interference criteria, as well as non-linear effects [16]. Relevant results were presented for either simple or aggregated protection distances from IMT Base Stations (BS) to FSS earth stations and the elevation angle: for angles between 5º to 30º the simple distance ranges from 13.8 km down to 8.2 km in urban scenarios, and 9.3 km to 5.1 km in urban ones [18]. In Brazil, the National Telecommunications Agency (ANATEL) conducted a study that determines that the IMT and FSS systems can coexist harmoniously depending on the characteristics of the IMT system and the specifications of the FSS receiver. They include the arrival angle for FSS services and how they affect the interference signals. However, the problem resides that in Brazil, low-quality TVRO satellite receivers could enter in a saturated state due IMT emission out of the band the Low-Noise Block (LNB) filter could not block. For this, the study concludes that 25MHz of the guard band has to be implemented between LTE and FSS operational frequencies [19].

A joint study between the Italian Ministry of Economic Development (MISE), the Ugo Bordoni Foundation (FUB) and Huawei, to determine the impact of an LTE-TDD radio base station on a domestic satellite system (Very Small Aperture) VSAT at a 3600 - 3800 MHz band, was presented in [20]. The study determined that a 26 MHz guard band is required to avoid interference in the case of IMT with 10 MHz bandwidth and FSS with a 36 MHz bandwidth. In [21], a deterministic study for China scenario is presented. It investigated in-band and adjacent interference scenarios and found that the appropriate frequency offset from the edge of the channel is 10 MHz for the downlink (DL) and 5 MHz for the uplink (UL). If LTE is an FDD system, the FSS operating band performs better if it is assigned adjacent to the LTE uplink. Besides, a protection distance of approximately 1 km is required. [22] presents a study of interference for IMT service in the 3.6-3.8GHz band. Results show that a guard band of 18MHz is sufficient for an I/N of -10dB for a macro cell, while 0 MHz are needed for small cells. A critical remark done is that the appropriate spectrum mask selection will reduce the chances of interference. A proposal of interference mitigation through the usage of cooperative beamforming from the satellite is presented in [23]. Another cooperative study to mitigate interference is presented in [24], [25]. In this study, a cooperative scheduling algorithm based on a game-theoretic framework adapts the IMT beamforming to reduce the interference levels. In [26], an interference mechanism using multiple-input multiple-output (MU-MIMO) spatial division multiple access (SDMA) is investigated.

Although the studies differ from each other regarding their methodologies and results, they all show that sharing spectrum between an FSS earth station and an IMT-A station, is not feasible, if a minimum protection distance or a guard band is not implemented.

III. Methodology

The methodological design consists of simulations to select the critical coexistence scenarios of the two mentioned services. Simulations were performed using ICS Telecom software [27] and evaluation of the interference to noise (IN) and permissible threshold degradation (TD) parameters described in the following sections.

A. Scenario definition

The coexistence scenarios for FSS and IMT services are depicted in Fig. 2. The continuous blue lines describe the desired signals while the red dashed present the interfering signals. Four interference scenarios are described: 1) LTE eNodeB (eNB) to FSS earth station, 2) LTE Users Equipment

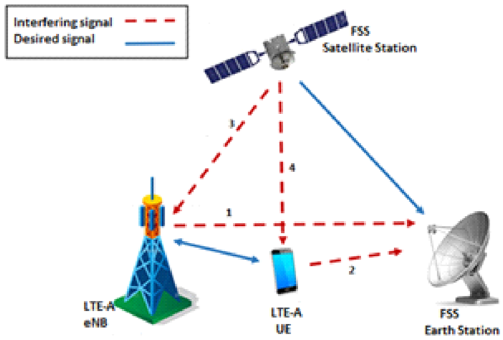

Fig. 2. Considered interference scenarios between LTE-A and FSS (1 = LTE-A eNB to FSS earth Station, 2 = LTE-A UE to FSS earth station, 3 = FSS satellite to LTE-A eNB, 4 = FSS Satellite to LTE-A UE.

(UE) to FSS earth station, 3) FSS satellite station to eNB and 4) FSS satellite to LTE (UE). Including the two transmission modes TDD and FDD, the location of devices (indoor or outdoor), the transmission environment (urban, suburban or rural) and the size of the cells (micro and macro); the total amount of interference scenarios sums up more than 60. To simplify the analysis, we select the eight more probable scenarios for the Colombian conditions listed in Table I, labelled from A1 to A4 and B1to B4, using only TDD mode, outdoor transmission and reception, and FSS technology. In discussion with the MinTIC and ANE officials, the following parameters were taken into account to reduce the number of interfering scenarios. The FDD configuration was ruled out based on the spectrum efficiency of TDD mode. Similarly, the indoor scenarios were deferred based on their lower interference probability. The resulting eight scenarios are fulfilling the recommendations posted in the Report ITU-R M.2292 [12].

We configure the simulation network in the ICS Telecom tool based on the parameters described in Table II. To this aim, we deployed simulation scenarios in the city of Bogota, Colombia. We simulate two known FSS stations in the urban and suburban areas of the city, receiving the signal from the SES-6 satellite. The ICS Telecom, as described in the next subsection, simulate scenarios based in the location of nodes and transmission parameters, and returns, in the interference case, the IN and TD parameters calculated from the received power levels. The propagation models for the simulation were ITU-R 452-16 and ITU-R 2001-2 [28], [29], in order to count for the satellite counterpart and the urban-suburban part of the simulations.

B. Simulation and evaluation tools

The ICS Telecom software allows planning radio communication networks, managing and optimizing the radio, frequency spectrum, and evaluating different technologies and its coexistence [27]. To perform the interference simulations, we vary the distance, the frequency and the elevation angle of the FSS terrestrial antenna to study the behavior of the elements involved in each of the selected scenarios.

TABLE I. TRANSMISSION PARAMETERS FOR LTE-ADVANCE AND FSS STATIONS

Parameter	LTE-A eNB	LTE-A UE	FSS Satellite	FSS Earth	Unit
Signal	LTE-A TDD	LTE-A TDD	DVB-S2	DVB-S2	-
Nominal Power	43 Suburban 40 Urban (1)(2)	26(1)(2)	40	-	dBm
TX Antenna Gain	18(1)	0(1)	50(4)	0	dBi
RX Antenna Gain	18(1)	0(1)	50(4)	+6.2, -1.6, -8.6(6)	dBi
Interference difference Angle	-	-	-	11, 22, 42	º
Tx and Rx Losses	0	0	2	0	dB
E.I.R.P	61 Suburban 58 Urban	26	90	-	dBm
Frequency	3664-3718(3)	3664-3718(3)	3718(4)	3718(4)	MHz
Antenna Height	30	1.5	35800000±0.03%	10	m
Bandwidth	20(1)	20(1)	36(5)	36(5)	MHz
Rx Threshold	2.33	7.33	0.1	0.1	dBuV/m
KTBF	-101	-101	-104.3	-104.3	dBm

(1) Report ITU.R M.2292 [12]. (2) Resolution 774/2018 ANE [30]. (3) Central frequency variable from 3655 to 3718. (4) SES-6 2016 [31]. (5) DVB-S2 [32] (6) Earth station Performance Requirements [33]

TABLE II. SELECTED SCENARIOS AND ITS NOMENCLATURE

Environment	LTE-A to FSS	FSS to LTE-A
Suburban (A)	**A1:** eNB to ES	**A3:** Sat to eNB
	A2: UE to ES	**A4:** Sat to UE
Urban (B)	**B1:** eNB to ES	**B3:** Sat to eNB
	B2: UE to ES	**B4:** Sat to UE

The interference simulation protocol responds to the variation tree described next. First, we switch between suburban (A) and urban (B) environments, where locations of the interfering and victims nodes were defined. Second, we present the interference scenarios that depend on the source of interference, whether it is from LTE-A to FSS or vice versa, and if the element involved in LTE-A is the eNB or the UE. For the third level of variation, two propagation models were considered (ITU-R 452-16 and ITU-R 2001-2) [28], [29]. The final level of variation describes the spectral movement.

Co-channel and adjacent band interference were analyzed here. While the FSS service was fixed in frequency (because FSS is the victim service), the IMT frequencies were variable. The difference from the LTE upper frequency and FSS lower frequency vary from -28MHz (co-channel) to +26MHz (adjacent band), as depicted in Fig. 3. The location of the victim nodes was located in a straight line following the axis of the satellite link, pointing towards the FSS ground station, ensuring maximum gain in the directivity of the antenna thus a maximum possible interference. We consider 20 separations between nodes following logarithmic increments between 100 m and 200 km. Also, according to the technology, we select the

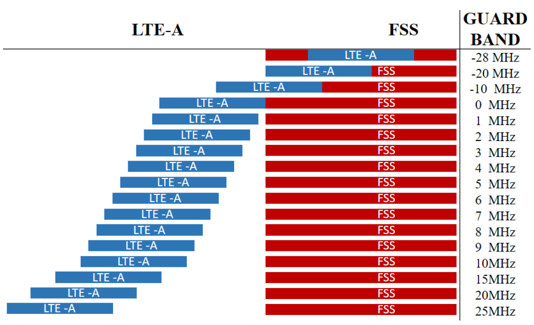

Fig. 3. Frequency variations for in band and adjacent band interference. Blue block = LTE-A, Red block = FSS

bandwidths for LTE-A and the FSS services as 20 MHz and 36 MHz respectively.

In addition, we evaluate three angles of the interfering signal, following the recommendations presented in [19]. In particular, the θ angle is defined as the difference between the axis of the pointing vector to the satellite, and the actual vector from the interfering signal. The relation between these angles and the actual impact in the received signal is dependent on the radiation pattern of the receiver antenna. We define the angles of 11º, 22º and 42º equivalent to 6.2 dBi, -1.6dBi and -8.6dBi in the antenna gain (for the FSS service) respectively. The antenna used in our simulations follows the gain equation (Gi= 32 - 25log (θ)) for angles smaller than 42º [34].

C. Evaluation Parameters

The interference measurement methodology was based on the evaluation of interference thresholds: harmful, tolerable and allowed, according to the cumulative distribution of the Interference to Noise Ratio (I/N) and the permissible Threshold Degradation (TD). The IN is the difference between the thermal noise and the interference signal (IN = I – kTBF) [35]. In the case of IN, the values are dependent on the sensitivity of the receivers and the percentage of interference allowed over a month. The recommendation ITU-R S.2199 defines a non-interfered system when IN is less than -12dB [15]. However, the threshold for harmful interference is dependent on how much interference is allowed throughout the month; for a maximum interference of 1% of the month, the threshold is extrapolated at -6.5dB. The TD is defined as the difference between the level of the wanted signal received for a given Bit Error Rate (BER) and the signal in the presence of interference for the same BER [36], and its value between 0 and 1 determines the tolerable interference range. Table III lists the threshold values for the different types of interference that can be used in the simulation analysis.

TABLE III. SELECTED SCENARIOS AND ITS NOMENCLATURE

Parameter	Threshold			Ref
	Harmful	***Tolerable***	***Allowed***	
IN	-6.5 < IN	-12.2<IN<-6.5	IN < -12.2	[35]
TD	1 < TD	0 < TD < 1	TD = 0	[36]

IV. RESULTS

The analysis of simulation data was discussed to analyze the case of "tolerable interference" from the parameters IN and TD. The following section discusses the impact of the guard bands and the θ angle into the protection distance, based on realistic simulation.

Fig 4, presents the comparison of protection distances from eNB using IN and TD parameters for the suburban and rural scenarios. The results showed that the PD for the cochannel interference (-28 to 0 MHz) is constant. The maximum value is 350 km for the A1 scenario with the IN parameter and 250 for the TD parameter. Similar behavior is found in the adjacent channel results. The PD is reduced while the guard band increases. In this case, the difference between the IN and TD parameters is reduced demonstrating a comparable performance between those parameters.

In order to found a relationship among the protection distances, the guard bands and the angles of the interfering signal, two generalizations had been made. First, we average the protection distances from the IN and TD parameters, knowing that the protection distances from IN are nearly 10% higher than TD results in the adjacent channel, and reduces with greater guard bands. Second, due to the vast numbers of simulation results for the analysis, the guard bands were grouped in six intervals. The first interval includes the co-channel interference band, in which the spectral differences of the center frequencies are negative (from -28 to 0 MHz) and then the bands from 1 to 5 MHz, 6 to 10 MHz, 11 to 15 MHz, 16 to 20MHz and 21 to 26 MHz.

The results of the protection distances for the guard band interval proposed using the IN and TD parameter are presented in Fig.5. The protection distances from the IN and TD parameter were very similar, particularly in adjacent band, and we plotted the average results between these parameters. The figure compares the results from different antenna angles.

The results for IN - TD presented suggest that the protection distance for the cochannel interference, the distances should be higher than 150 km and 140 km for suburban and urban scenarios respectively in interference from eNB. Comparatively, these values are much lower from UE, where distances should be 2.7 km and 2.2 km respectively. As expected, the protection distances are reduced with the increment of the guard band. Results showed a reduction average of 29.5 km each 5 MHz of guard band, for cases A1 and B1.

When the angle θ increments, the incidence of the interference signal decreases, thus the protection distances. For the cochannel interference (brown box in Fig. 4.) in A1, the PD decreases from 278 km (θ=11º) to 215 km for θ=22º and 150 km for θ=42º respectively. Similarly, in B1, the PD decreases from 244 km down to 181 km and 141 km for θ=11º, θ=22º and θ=42º respectively. The behavior is similar for adjacent channel interference. An average reduction of 50 km in the protection distance is presented for each angle variation. This behavior leads to a PD range from 278 km down to 17.5 km for A1 and 244 km down to 12.5 km in B1 depending on the guard band and the incidence angle of the interfering signal. Hence, the interference value is highly dependent on the angular position, in addition to the distance between the victim and interfering elements, and the guard band configured.

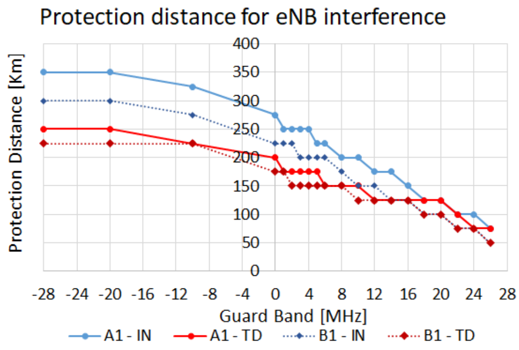

Fig. 4. Comparions of Protection Distances for eNB Interfernce in worst case scenarios. Blue Lines using IN, Red lines using TD. Continued lines for Suburban scenario, Doted lined for urban scenario.

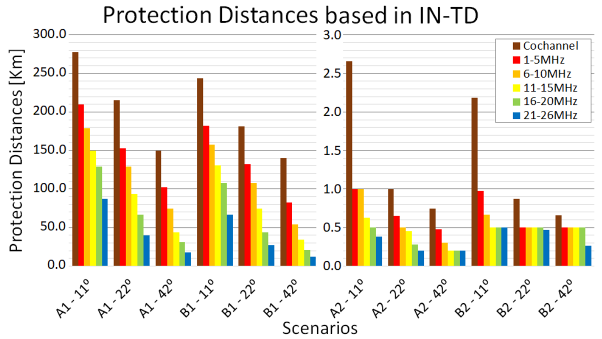

Fig. 5. Protection distances for Tolerable interference for all scenarios based in IN and TD, for different discrete guard bands. Leftside: Interference from eNB. Rigthside: Interferecne from UE.

For scenarios where the interference node is the UE (A2 and B2), the results are more conservative, with protection distances from 2.7 km in co-channel interference down to 200 m for 42º incidence angle and 21 to 25 MHz guard band.

Table IV presents a summary of the recommended protection distances for the different guard bands and interference angles for the worst-case scenarios. It can be seen that the PD between the eNB and the UE is almost 200 times greater in both rural and suburban scenarios, for adjacent channel interference. For the co-channel is only 100 times. Moreover, between the suburban and rural scenarios, the suburban needs nearly 17%±3% more protection distance than the rural for the eNB case, and 9%±5% for the UE case.

TABLE IV. PROTECTION DISTANCES FOR TOLERABLE INTERFERENCE FOR A1, A2, B1, B2 SCENARIO USING IN AND TD.

Scenarios	Co-channel	Adjacent Band				
		1-5MHz	*6-10MHz*	*11-15MHz*	*16-20MHz*	*21-26MHz*
A1 (11º)	278 km	210 km	179 km	150 km	129 km	88 km
A1 (22º)	215 km	153 km	129 km	94 km	67 km	40 km
A1 (42º)	150 km	103 km	75 km	44 km	31 km	18 km
A2 (11º)	2650 m	1000 m	1000 m	625 m	500 m	380 m
A2 (22º)	1000 m	650 m	500 m	450 m	280 m	200 m
A2 (42º)	750 m	480 m	300 m	200 m	200 m	200 m
B1 (11º)	244 km	183 km	158 km	131 km	108 km	67 km
B1 (22º)	181 km	133 km	108 km	75 km	44 km	28 km
B1 (42º)	141 km	83 km	54 km	35 km	21 km	13 km
B2 (11º)	2125 m	975 m	665 m	500 m	500 m	500 m
B2 (22º)	875 m	500 m	500 m	500 m	500 m	465 m
B2 (42º)	655 m	500 m	500 m	500 m	500 m	265 m

V. Conclusions and Future Work

Coexistence between LTE-FSS services is only possible when the receiving earth station is located beyond the protection distance. Logically, the eNB stations generate more interference than the UE nodes. It is reflected in the protection distances that are around 100 times greater for the cochannel interference and nearly 200 times for the adjacent channel interference. However, the mobility and the omnidirectional behavior of UE antennas could present short-term interference more significant than the eNB node. The interference received in an FSS earth station will depend strongly on the angle of arrival of the interference signal compared with the vector of the central globe. Our results show that for angles of $\theta=11^o$, $\theta=22^o$ and $\theta=42^o$, the protection distance could be reduced from 210 km to 153 km and 103 km in the immediate adjacent band interference (1-5MHz) suburban scenario. An average of 50 km distance reduction for each angle change is found, for eNB interfering signals. In Colombia, critical scenarios rarely occur due to the characteristics of the FSS satellites on which Colombian stations are connected, i.e., the elevation angles of most Colombian FSS earth stations are greater than 60^o, reducing the probability of direct interferences in high gain angles. This is important because of even the fact that protection distances in the worst cases are larger than 200 km, realistic cases could require 100 km of less depending on the actual geometry between LTE and FSS nodes. The PD obtained in our simulations (Table IV) for the range of 21 to 26MHz for scenarios A1 and B1, under similar conditions, are very close to the values of Case #10 (Annex 10) [16], where found distances of 30 km with GB of 25MHz and 24.5MHz, respectively.

The implementation of guard bands is essential to reduce the protection distance as well. Results show that introducing guard bands of 5MHz reduced de protection distance by an average of 25.5 km ± 5km each band for the eNB interference scenarios, and an average 100m for the UE scenarios. The relation between the protection distances and the guard bands will aid the administration in defining the channelization of the IMT services in the 3.5GHz bands. It is clear that a proper knowledge of the location and angles of FSS earth stations and LTE nodes, in coordination with guard band allocation will allow proper coexistence of these services.

The future work will include emulations and implementations of laboratory tests to evaluate the implication of different angles to more realistic scenarios, including also proper and detailed transmission masks of FSS and LTE and the inclusion of proper RF filters. Also, other interference mitigation strategies for FSS services may be implemented like adaptive antenna array installation, shielding of FSS earth stations, application of RF filters in the LNA of the FSS receiver, among others. Realistic dynamic frequency allocation techniques including other mitigation techniques should be studied to optimize the usage of the frequency band minimizing the interference probability. Finally, we recommend that for future work it could be included the analysis of aggregate interference I/ N (Case #9, Annex 9) [16], because our study only includes a single entry interference I/N.

References

[1] ITU, 'Final Acts World Radio Conference 2015', ITU, Geneva, 2015.

[2] GSMA, 'Considerations for the 3.5 GHz IMT range: getting ready for use'. May-2017.

[3] L. F. Abdulrazak, 'Coexistence of IMT-Advanced Systems for Spectrum Sharing with FSS Receivers in C-Band and Extended C-Band .', in *Coexistence of IMT-Advanced Systems for Spectrum Sharing with FSS Receivers in C-Band and Extended C-Band*, L. F. Abdulrazak, Ed. Cham: Springer International Publishing, 2018, pp. 9–41.

[4] Weidong Wang, Fei Zhou, Wei Huang, Ben Wang, and Yinghai Zhang, 'Coexistence studies between LTE system and earth station of fixed satellite service in the 3400–3600 MHz frequency bands in China', in *2010 3rd IEEE International Conference on Broadband Network and Multimedia Technology (IC-BNMT)*, Beijing, China, 2010, pp. 1125–1130, doi: 10.1109/ICBNMT.2010.5705265.

[5] GSA, 'The Future of IMT in the 3300-4200MHz Range.pdf'. Jun-2017.

[6] ITU, 'Rec ITU-R M.1036-6: Frequency arrangements for implementation of the terrestrial component of International Mobile Telecommunications in the bands identified for IMT in the Radio Regulations', Geneva, Switzerland, Oct. 2019.

[7] 3GPP, '3GPP TS 38.101-1: 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone (Release 15)'. Jun-2018.

[8] ITU, *Radio Regulation Articles - Edition 2016*, 4 vols. Geneva, Switzerland, 2016.

[9] ANE, 'Cuadro Nacional de Atribución de Bandas de Frecuencias - 2018', p. 389, 2018.

[10] ITU, *World Radiocommunication Conference 2019 (WRC-19) - Provisional Final Acts*. Geneva, Switzerland, 2019.

[11] ITU, 'Rec ITU-R M.2012-4: Detailed specifications of the terrestrial radio interfaces of International Mobile Telecommunications-Advanced (IMT-Advanced)', Nov. 2019.

[12] ITU, 'Rep ITU-R M.2292-0: Characteristics of terrestrial IMT-Advanced systems for frequency sharing/interference analyses.', Dec. 2013.

[13] ITU, 'Rep ITU-R M.2109: Sharing studies between IMT-Advanced systems and geostationary satellite networks in the fixed-satellite service in the 3 400-4 200 and 4 500-4 800 MHz frequency bands', 2007.

[14] ITU, 'ITU-R S.2150. An interference reduction technique by adaptive-array earth station antennas for sharing between the fixed-satellite service and fixed/mobile services. S Series – Fixed satellite service.', ITU-R Radiocommunication Sector of ITU, 2009.

[15] ITU, 'Rep ITU-R S.2199: Studies on compatibility of broadband wireless access systems and fixed-satellite service networks in the 3 400-4 200 MHz band', 2010.

[16] ITU, 'Rep ITU-R S.2368-0: Sharing studies between IMT-Advanced systems and geostationary satellite networks in the FSS in the 3 400-4 200 MHz and 4 500-4 800 MHz frequency bands', 2010.

[17] ANE, 'Resolucion 0181 de 2019', Apr. 2019.

[18] FCC, *FCC 05-56. Report and Order*. Washington D.C.: FCC, 2005.

[19] L. C. Fernandes and A. Linhares, 'Coexistence conditions of LTE-advanced at 3400–3600 MHz with TVRO at 3625–4200 MHz in Brazil', *Wireless Networks*, vol. 25, no. 1, pp. 105–115, Jan. 2017, doi: 10.1007/s11276-017-1544-8.

[20] Italian Ministry of Economic Development and JCR, 'Sharing analysis in a live LTE network in the 2.3-2.4 GHz band.' 2016.

[21] W. Wang, F. Zhou, W. Huang, B. Wang, and Y. Zhang, 'Coexistence studies between LTE system and earth station of fixed satellite service in the 3400-3600 MHz frequency bands in China.' 2010.

[22] Transfinite systems, 'Report for GSMA on the mitigations required for adjacent channel compatibility between IMT and ubiquitous FSS Earth Stations in the 3.4 – 3.8 GHz frequency band', Aug. 2019.

[23] J. Du, C. Jiang, H. Zhang, X. Wang, Y. Ren, and M. Debbah, 'Secure Satellite-Terrestrial Transmission Over Incumbent Terrestrial Networks via Cooperative Beamforming', *IEEE Journal of Selected Areas in Communications*, vol. 36, no. 7, pp. 1367–1382, 2018.

[24] F. Guidolin, M. Nekovee, L. Badia, and M. Zorzi, 'A cooperative scheduling algorithm for the coexistence of fixed satellite services and 5G cellular network', in *2015 IEEE International Conference on Communications (ICC)*, 2015, pp. 1322–1327, doi: 10.1109/ICC.2015.7248506.

[25] F. Guidolin, M. Nekovee, L. Badia, and M. Zorzi, 'A study on the coexistence of fixed satellite service and cellular networks in a mmWave

scenario', in *2015 IEEE International Conference on Communications (ICC)*, London, 2015, pp. 2444–2449, doi: 10.1109/ICC.2015.7248691.
[26] J.-W. Lim, H.-S. Jo, H.-G. Yoon, and J.-G. Yook, 'Interference mitigation technique for the sharing between IMT-advanced and fixed satellite service', *Journal of Communications and Networks*, vol. 9, no. 2, pp. 159–166, Jun. 2007, doi: 10.1109/JCN.2007.6182835.
[27] ATDI, *EV ICS telecom manual*. Paris, FRANCE, 2017.
[28] ITU, 'Rec ITU-R P.452-16: Prediction procedure for the evaluation of interference between stations on the surface of the Earth at frequencies above about 0.1 GHz', p. 59, Jul. 2015.
[29] ITU, 'Rec ITU-R P.2001-3: A general purpose wide-range terrestrial propagation model in the frequency range 30 MHz to 50 GHz', Geneva, Switzerland, Aug. 2019.
[30] ANE, 'Resolucion 774 de 2018':, Bogota, Colombia., Dec. 2018.
[31] Eutelsat Américas, 'Standard for the operation of satellite services.', Coral Gables. FL. USA, Jun. 2006.
[32] Morello, A. and Reimers, U., 'DVB-S2, the second-generation standard for satellite broadcasting and unicasting', *International Journal of Satellite Communications and Networking*, vol. Vol. 22, no. No. 3, 2004.
[33] SES, *Earth Station Performance Requirements*. The Hague, THE NETHERLANDS, 2006.
[34] ITU, 'ITU-R S.465-6. Reference radiation pattern of earth station antennas in the fixed-satellite service for use in coordination and interference assessment in the frequency range from 2 to 31 GHz', Geneva, Switzerland, Jan. 2010.
[35] ITU, 'Rec ITU-R S.1432-1: Apportionment of the allowable error performance degradations to FSS hypothetical reference digital paths arising from time invariant interference for systems operating below 30 GHz'. 2006.
[36] HCM program, 'Harmonised Calculation Method (HCM) Agreement for some european countries.', Bonn, Germany, 2019.