Survey on Coexistence of Terrestrial Television Systems and Mobile Fixed Communications Networks in Digital Dividend Bands

Hussein Taha, Péter Vári, Szilvia Nagy

***Abstract*—Due to the scarcity of frequencies required to develop digital infrastructure in broadband, can only be offered by releasing frequency bands that are already allocated and utilized by other services. To meet this requirement, the International Telecommunication Union released the terrestrial broadcast spectrum for mobile fixed communications networks in two phases, as known the first and second digital dividends. An upcoming challenge is the effect of the presence of more services in the same or adjacent bands. Hence, it is critical to offer adequate radioprotection against potentially harmful interference in practice, whether on terrestrial television systems or mobile fixed broadband networks in digital dividend bands. This article presents a survey on compatibility studies between mobile fixed communications networks and terrestrial television networks in the 700/800 MHz frequency ranges. We present a brief general overview of the methodologies used to investigate coexistence, including computer simulations, laboratory measurements, and field measurements, as well as a review of the literature relevant to each methodology.**

***Index Terms*— Coexistence, Interference, Terrestrial Television, MFCN, 700 MHz**

I. Introduction

In the near future, there will be an increase in users and innovative services. As a result, data traffic using mobile radio connections is predicted to grow exponentially [1, 2]. Thus, the spectrum that these services would consume will not be sufficient to meet the growing demand [2].

Due to the shortage of spectrum technically suited for broadband mobile service, national administrations and international organizations are investigating new and more flexible methods to release frequency bands for network development. In this regard, the International Telecommunication Union (ITU) released the 790–862 MHz rang (hereinafter: 800 MHz frequency band) of the Ultra High Frequency (UHF) range, traditionally used for television broadcasting, to mobile services, also commonly known as Digital Dividend 1 (DD1) [3, 4, 5]. However, because of the growing demand for mobile broadband and the necessity to unify spectrum use in order to create a digital single market. In 2015, the ITU released the next band 694–790 MHz (hereinafter: 700 MHz frequency band), also known as Digital Dividend 2 (DD2) [3, 4, 5], as shown in Figs. (1), (2):

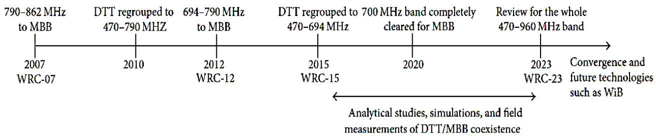

Fig. 1. Timeline of regulatory rulings in Europe governing the use of the UHF TV transmission band.

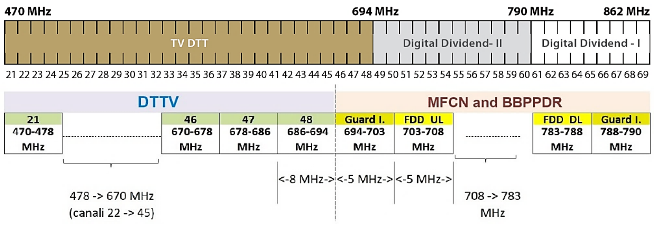

Fig. 2. Use of UHF spectrum in Europe after the 700 MHz range is released for Mobile Broadband.

The spectrum in the frequency range of 700 MHz is very highly desired in terms of creating broadband mobile services because its physical properties allow coverage of sparsely inhabited rural regions at minimal cost via networks utilizing Mobile/Fixed Communication Networks (MFCN) [5, 6], as shown in Fig. (3). Moreover, it is suitable for supporting 5G services and will also assist develop other future creative services like connected cars, onboard entertainment, remote health care, and smart energy grids [5, 6].

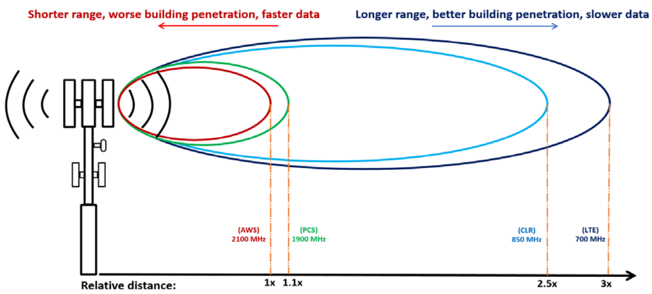

Fig. 3. 700 MHz delivers superior coverage

The impending concern with deploying MFCN, particularly 4G/5G networks in the digital dividend bands, is that interferences in nearby radio frequency channels used for digital terrestrial television may arise. Furthermore, terrestrial television causes significant interference in the digital dividend bands for MFCN. Many coexistence experiments have been conducted to assess the interference of MFCN

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signals with terrestrial television and vice versa [6]. Different approaches to investigate terrestrial television-MFCN coexistence were presented in prior research works to assess the interference problem, including mathematical calculations, computer simulations, laboratory testing, and field measurements under actual conditions.

This paper reviews the literature on coexistence studies between terrestrial television networks and MFCN networks according to the methodologies used. Section II. surveys several research papers which used statistical modelling and computer simulations of various interference scenarios. Section III. discusses how to emulate the coexistence scenarios in the laboratory and make laboratory measurements and related research works. Section IV. presents how to validate the obtained results through field measurements using professional equipment and related research studies. Section V. concludes this paper.

II. Statistical Modelling and Computer Simulations

In order to analyze interference between terrestrial television networks and MFCN, most research studies based on statistical modelling and computer simulation have employed the SEAMCAT (Spectrum Engineering Advanced Monte Carlo Analysis Tool) software tool. SEAMCAT is an effective tool for determining the level of electromagnetic compatibility between services and ensuring that they can work together without interruption [7].

A. Simulation tool

SEAMCAT is a statistical software simulation tool that was first released in Jan-2000 and gradually developed in several phases as a cooperation between national regulatory administrations, the European Communications Office (ECO), and industry. SEAMCAT examines the possible interference when several different radio systems operate in the same or adjacent bands using the Monte-Carlo calculation method [8]. Monte Carlo simulations are the most effective way of dealing with interference's stochastic character. The researchers have access to all simulation models and parameter assumptions for both MFCN and terrestrial television systems, as well as the methodologies and scenarios pre-defined by the regulatory agencies for the different radio systems.

The victim link and the interfering link are the two key links in the SEAMCAT general scenario. Fig. (4) shows how each link is made up of two elements [8]. Through the software interface, the user may configure the technical specifications and settings for each considered scenario.

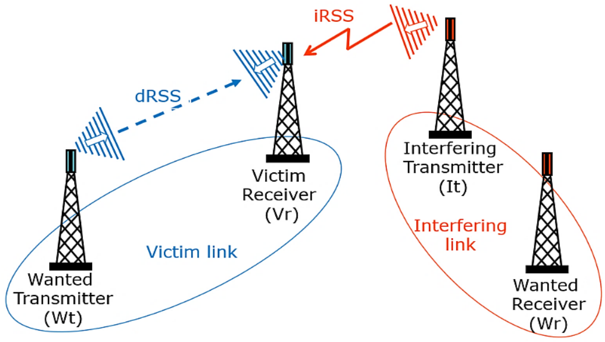

Fig. 4. SEAMCAT general scenario

The tool functions by generating random spatial and temporal distributions of desired and interference signals, allowing realistic scenarios to be estimated using a variety of random variables such as the location of the interferers in relation to the victim, desired signal strength, throughput, lost packets, high latency, victim and interferer channels, and so on. Each parameter of the interfering and victim links may be set as a constant or variable in the program interface. The probability of systems interference is determined using these parameters as the average ratio of wanted and unwanted (interfering) signals in the victim receiver for a significant number of samples/events (more than 20,000 samples) [8, 9]. In this approach, the tool may be used to perform electromagnetic compatibility evaluations and extensive assessments of the likelihood of interference between radio systems, assisting in the resolution of various spectrum engineering issues and the harmonic coexistence of systems.

B. Interference scenarios and compatibility assessment

To begin, presumptions, simulation techniques, and scenarios described for simulation models and variables in both MFCN, and terrestrial television systems must all be agreed upon. Simplex systems used in terrestrial television only have one connection (downlink), while MFCN has two devices: the Base Station (BS) and the User Equipment (UE). Both devices are transmitters and receivers, allowing for downlink and uplink connections. Then, for each case study, the technical parameters, and specifications of terrestrial television and MFCN (especially 4G/5G) are defined for simulation modelling using the standardized SEAMCAT specification.

The scenarios are created by considering the positions of the transmitters and receivers, as well as the antenna properties. The simulation results for each scenario are then organized independently in SEAMCAT. The interference is then assessed using the following criteria: dRSS (desired received signal strength) and iRSS (interference received signal strength) which are obtained by SEAMCAT, Protection Ratios (PRs), Carrier to noise ratio, Guard Band (GB) that separate the two interfering systems, antenna gain, overall sensitivity threshold of TV receiver, propagation loss, and centre frequency, etc. Finally, the simulation results will contribute to some conclusions concerning the terrestrial television-MFCN coexistence requirements in the considered frequency range.

C. Review of related works

This section provides an overview of most of the research works in the area of compatibility analysis between MFCN and terrestrial television systems in the 700/800 MHz band using computer simulations.

Thera are many coexistence studies that have been published on Digital Terrestrial Television (DTTV) and MFCN [10-24] [27, 28], while few papers on coexistence studies between Analogue Terrestrial Television (ATTV) and MFCN in 700/800 MHz band were found [25, 26].

In [10, 11], the authors tested and validated the SEAMCAT simulation tool for evaluation of the interference between digital terrestrial television and Long-Term Evolution (LTE) system in the 700 MHz frequency band, by comparing the outputs of SEAMCAT with the measured results for scenarios that replicate the experimental setups. The authors found that SEAMCAT satisfies the goals of this area of testing since it allows them to simulate various scenarios that would be difficult to perform using field measurements. They investigated the impact of distance between systems, transmission power, the number of interferers, and other factors on potential interference scenarios between digital terrestrial television systems and LTE.

In [12], the authors analyze permissible interfering field strength levels for co-channel sharing scenarios in the 700 MHz band between DTTV and International Mobile Telecommunications (IMT) systems (from DTTV to IMT and vice versa), as well as needed minimum separation distances for both IMT mobile systems directions (uplink and downlink). Mutual interferences are observed to be particularly high in the lower 700 MHz band (uplink), where cellular handsets are closer to DTTV receivers than base stations. While the situation is considerably better in the upper part of the 700 MHz band (downlink), where mutual interferences are smaller and may be mitigated by topographical impediments and/or correct modification of practical emission settings. It should be mentioned that co-channel sharing scenarios between DTTV and IMT mobile systems in the 700 MHz band are a unique situation that can only occur near the border of two adjacent nations, such as the Hungarian-Ukrainian border.

In [13, 14], the primary purpose was to evaluate the interference caused by the LTE transmitter into the DTTV service in the adjacent band. The procedure for the avoidance of harmful interference to DTTV receivers in the 700 MHz band is the ability of the LTE transmitter to avoid out-of-band emissions on the one hand, and the ability of the DTTV receiver to attenuate interference received out-of-band on the other hand.

In [15-17], the electromagnetic compatibility of DTTV and LTE system in the 700 MHz band was evaluated utilizing various methods, namely the Monte Carlo approach by SEAMCAT, Minimum Coupling Loss (MCL) method, and calculations of coordination trigger field strength established by GE06 agreement. The results showed that in the frequency range of 700 MHz, a minimum distance between LTE and DTTV is required to keep the appropriate performance level of DTTV systems and the LTE receiver. In order to reduce the separation distance between LTE and DTTV systems and ensure compatibility in the 700 MHz band, the authors proposed using various interference mitigation methods, such as antenna discrimination, tilt antennas, adjusting radiation pattern and antenna height in LTE-BS, reducing power levels of the interfering transmitter in the adjacent bands, etc.

In [18], computer simulations were performed to assess the impact of LTE signal interference on digital terrestrial television services when the channels are distributed by collective antenna systems with a wideband amplifier.

In Nigeria [19, 20], the coexistence of LTE and Digital Video Broadcasting-Second Generation Terrestrial (DVB-T2) in the UHF television band has been evaluated using SEAMCAT software. According to simulation results in [19], inserting a 1 MHz guard band decrease interference by 64.76 percent with a single interferer and an average of 20.91 percent with several interferers when the DVB-T2 transmitter and receiver are separated by 5 kilometers. Further increase in guard band did not result in any considerable reduction in the probability of interference. Therefore, DVB-T2 may be deployed in adjacent bands with LTE when the separation distance between DTTV transmitter and receiver is less than 5 km, but not when LTE base stations are dense in the DVB-T2 coverage area. The research in [20] focused on managing interference from the closest cellular base station with external fixed digital TV reception in the digital dividend bands. The interference of LTE downlink operating in the 700 MHz band with digital TV channels 17 (490 MHz) and 51 (693 MHz) was investigated as a function of the separation distance between the cellular base station and the TV receiver. Both systems may coexist in the digital dividend band, according to simulation results, while maintaining the minimum allowable protective distance for each channel. For the same separation distance, channel 51 will suffer more interference than channel 17 since it is closer to the cellular broadcast range.

In [21], the authors considered the coexistence scenario of DTTV and MFCN in adjacent frequency bands in the regions bordering Italy. The level of interference caused by digital TV systems into MFCN channels was calculated, and it was observed that the separation distances required to secure MFCN system protection from DTTV interference are more than 100 kilometers.

The work in [22] presented a detailed analysis to evaluate the effect of the interference generated by DTTV in the LTE system operating in adjacent channels with bandwidths of 5 MHz, 10 MHz, and 20 MHz, using the Monte Carlo technique. The authors analyzed the LTE channel capacity loss and the Bit Error Rate (BER) applying the Quadrature Phase Shift Keying (QPSK) modulation scheme, in order to quantify the influence of the interference. The results showed that the LTE performance can be affected by interference from DTTV in the 700 MHz band that may result in transmission error and channel capacity losses of the LTE system. Furthermore, the antenna height of the victim system (LTE) does not cause any major influence on the interference impact from DTTV. Suggested solutions in this work to reduce noise and transmission errors are decreasing the DTTV transmission power and respecting the minimum distance between LTE base stations and DTTV.

The authors in South Africa [23] indicated a mechanism for the coexistence of DTTV and LTE in the 700/800 MHz bands, by installing a terrestrial digital TV transmitter and a cellular base station on the same tower. The advantages of this mechanism include, on the one hand, are maintaining constant protection ratios between the TV broadcast and the cellular signals, and on the other, saving the expenses of installing and maintaining antennas dedicated to each service. However, due to the severe limits of minimum separation distances, ensuring coexistence for low-power TV transmitters will be more challenging.

Some research works employed the MATLAB application rather than the SEAMCAT tool for terrestrial television-MFCN coexistence issues [24]. The authors of [24] employed MATLAB computer simulations to investigate the impact of cellular downlink interference on home digital TV receivers. The DVB-T system was simulated in MATLAB with ideal channel estimation, and the cellular downlink in Multiple

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Input Multiple Output model (2×2 MIMO) was simulated using the LTE Downlink Link Level Simulator tool. According to the results, the protection ratio and the minimum separation distance between LTE-BS and digital TV receivers can be reduced using proper Spectral Emission Masks (SEMs) for the cellular downlink broadcast.

In Indonesia [25], and South Africa [26], the mutual interference between analogue terrestrial television and the LTE system in the 700 MHz band was analyzed using SEAMCAT. To ensure the proper coexistence of both systems, the minimum protection distances and guard bands were determined. According to the GE06 Agreement, analogue transmissions were discontinued after 2015 in ITU Region 1, which includes Europe, Africa, Mongolia, the former Soviet Union, and the Middle East. In this regard, the Indonesian government has set a target of the end of 2022 for the transition to digital broadcasting [27]. As a response, the authors in [27] adopted a plan for deploying 5G networks in the digital dividend bands following the analog switch-off. They investigated the coexistence of digital terrestrial television systems and 5G networks in the new dividend band using the SEAMCAT simulation tool. According to the results, a Guard Band must be provided, and a minimum separation distance must be maintained to ensure the electromagnetic compatibility of the two systems in the 700 MHz band. Later, in Indonesia, another study was undertaken using Monte Carlo simulation to determine the protection ratios to protect primary users of digital terrestrial television from other devices utilizing the TV white spaces [28].

III. Laboratory Measurements

This section expands on the description of coexistence scenarios between terrestrial television networks and MFCN in the UHF band in a controlled laboratory environment. The parameters are based on actual device performance, and the results are presented with an examination of the impact of different factors.

A. *Coexistence scenarios*

The following assumptions are used to classify coexistence scenarios: The terrestrial television system, as previously stated, is a simplex system with only one connection (downlink), and the signal is received by an external rooftop antenna or a portable indoor antenna. Both uplink and downlink are available in MFCN systems. As a result, both the base station and the user equipment (whether inside or outside the building), must be considered. Fig. (5) shows critical coexistence scenarios considered in one of the relevant studies [29].

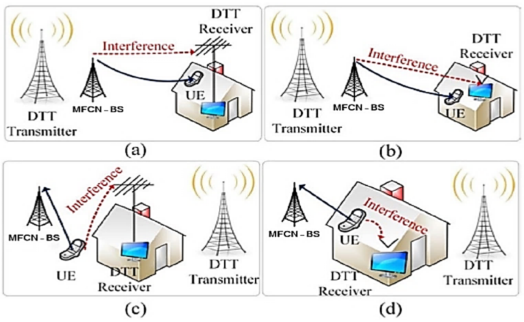

Fig. 5. Critical coexistence scenarios for MFCN (downlink/uplink) and DTTV reception (fixed outdoor/portable indoor) [29].

B. *Methodology*

Most of the reference studies that adopted the laboratory measurements methodology for coexistence investigations used linear devices based on the ITU-Report BT. 2215-4 [30]. The interference Protection Ratio (PR) is measured under laboratory conditions, then the link budget is analyzed using the calculated PRs to figure out the maximum levels of interference in worst-case coexistence scenarios.

The devices used include vector signal generators with channel emulation option (or independent signal generators and a channel emulator), digital signal generator, vector network analyzer, band-pass filter, isolator, TV sets, and set-top boxes, as illustrated in Figs. (6), (7).

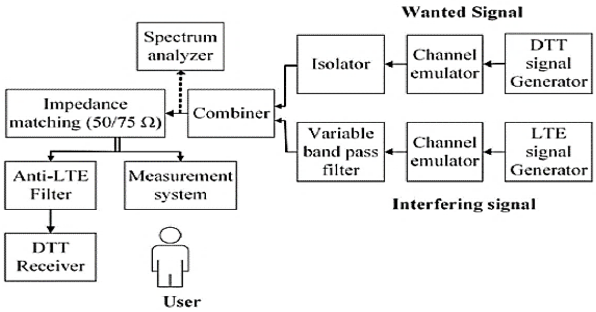

Fig. 6. Setup for coexistence investigations of DTTV and MFCN (LTE) in the laboratory environment [29]

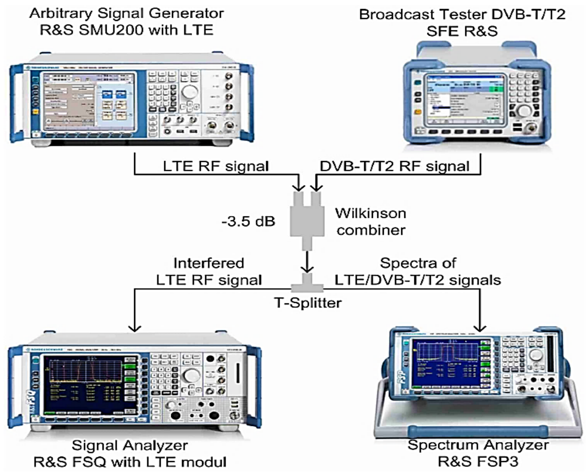

Fig. 7. LTE vs. DVB-T2 - laboratory measurement system [31]

The protection ratio is defined as the minimum ratio of the desired signal to the undesired signal at the RF receiver input in decibels (dB) to achieve specified reception quality standards [32]. A link budget analysis in communications and networking is a written description of all power gains and losses to determine the received power strength. In most applications, power gains and losses are indicated in (dB).

C. *Review of related works*

Here, we introduce some research works related to compatibility analysis between MFCN and terrestrial television systems in digital dividend bands using laboratory measurements.

The authors of [29, 33] used laboratory measurements to evaluate electromagnetic compatibles of LTE and DTTV in 700/800 MHz bands. In [33], Measurement of protection ratios and link budget analysis were used to investigate critical interference scenarios between LTE uplink and

DTTV in the 700 MHz band. In a portable indoor DTTV reception scenario, the key objective was to obtain the required minimum separation distances between the LTE user equipment and the TV receiver for various LTE user equipment powers. In addition to establishing if a low band filter was necessary for a fixed outdoor DTTV reception scenario. The analysis was expanded in [29] to include most of coexistence cases in both frequency bands (700/800 MHz). The authors examined the effect of the guard band as well as the use of a low pass filter. Furthermore, LTE signal factors such as varied bandwidths and traffic loads were considered. According to the results, avoiding interferences in worst-case scenarios is extremely challenging, hence high-quality criteria are recommended for the scenario under consideration.

In [31], the authors have examined the effect of the digital terrestrial television system on LTE downlink in the 800 MHz band. The laboratory measurements were performed considering the factors that directly affect the performance of LTE downlink such as the modulation schemes, bandwidths, and different traffic loads. The performance of LTE-DL services was evaluated according to the Carrier-to-Noise ratio (C/N) and Error Vector Magnitude (EVM).

In various interference cases, a low-pass filter has been utilized to reduce MFCN interferences into digital TV channels in the broadcasting spectrum [34, 35, 36]. The LTE interference effect on DVB-T channel 56 in the 800 MHz band was discussed in the article [34]. The interference scenario was emulated in the laboratory using an innovative RF band stop filter, manufactured in microstrip technology, then the authors verified the practical effectiveness of the RF band stop filter in a real-world interference scenario in Portugal. Also, a low-pass filter was designed for use in the TV receiver in Brazil [35], and it was tested with a vector network analyzer and found to be in good agreement with simulations. An efficient anti-LTE filter was recently developed in Spain utilizing microstrip technology and a Complementary Split Ring Resonator (CSRRs) [36]. Due to its integrated design without lumped elements, this filter provides lower production costs, fine-tuning, efficient coupling, and response stability as compared to conventional anti-MFCN filters. Furthermore, this filter may be utilized without modifications in both indoor and outdoor TV reception modes. The proposed designed filter's practical effectiveness was demonstrated by a comparison of simulated results and measured outcomes.

The obtained laboratory results in [37] indicated that LTE-downlink interference had a minor impact on various DVB-T2 system configurations in the 800 MHz band for portable indoor reception. The protection ratio parameter was used to assess overall performance while examining the various bandwidths and LTE-DL traffic loads.

The authors in [38] presented solutions to mitigate the influence of LTE downlink emissions on digital terrestrial TV channels in the 800 MHz frequency. The proposed appropriate countermeasures are the installation of a masthead amplifier in the Master Antenna Television system (MATV) plant to produce amplification of TV signals in order to avoid blind DVB-T channels, plus insertion of LTE filter to mitigate interference effects.

In [39] laboratory measurements were performed in an isolated environment to examine the effect of LTE uplink interference on coaxial cables between the TV set to the digital TV aerial socket. The authors examined the shielding attenuation properties of 10 different antenna coaxial cables and found that best-to-worst cable variances are around 60 dB. According to the results, LTE UE uplink interference into the coaxial cable is caused by a combination of factors, including the use of a low-quality coaxial cable and the synchronization of transmission digital TV and user equipment in close channels.

The reference study in [40] highlighted a particular case that goes beyond coexistence by allowing (LTE-A) and (DVB-T2) technologies to share the spectrum in the same location. The authors examined the scenario of using TV white spaces by indoor LTE-A femtocells in a rooftop DVB-T2 reception model. The scenario was emulated in the laboratory then verified in the field.

In a laboratory setting in Cuba [41], the researchers modeled numerous mutual interference scenarios to determine protection ratios and overload thresholds between analog and digital terrestrial TV systems and the LTE system in the 700 MHz band. The scenarios were configured based on the various bandwidths and traffic loads of the LTE signal, as well as the frequency offset between the desired signal and the interfering signal in the co-channel and adjacent channel, which can be up to 100 MHz. The findings of the investigation indicated that the analog terrestrial TV system is 14 dB more affected by LTE system interference in both the adjacent and common channels than the digital terrestrial TV system. Digital terrestrial TV, on the other hand, produces 9 dB more interference in LTE user equipment than analog terrestrial TV in the co-channel. The results of this study can be used as a reference for field measurements under similar interference conditions.

IV. Field Measurements

This section addresses the field evaluation of terrestrial television systems and MFCN coexistence in digital dividend bands. Radio signal measurements are performed in a real-world working environment using professional equipment to produce accurate results for determining the level of electromagnetic compatibility between the radio systems under consideration.

A. Characterization of field measurement scenarios

Due to limitations of field measurement conducting compared to computer modelling and laboratory measurement, field measurement scenarios are commonly created just to represent critical coexistence scenarios, by following these steps: The relevant field measurement locations for the considered situation are determined after an initial measurement is done to assess the level of terrestrial television and MFCN transmission. Furthermore, it must be guaranteed that no unsuitable phenomena exist at the chosen site that contradict the theoretical hypotheses and impair the measurement findings. The link budget is analyzed to determine the gains and losses of transmitted signals, considering a variety of factors, such as signal propagation type, coverage pattern, separation distances between antennas, antennas heights, antenna tilt level, TV receiver sensitivity, and so on.

Figs. (8), (9) show general interference situations evaluated in most of the relevant research [42], which include: interference from MFCN over terrestrial television receivers, and interference from terrestrial television over MFCN.

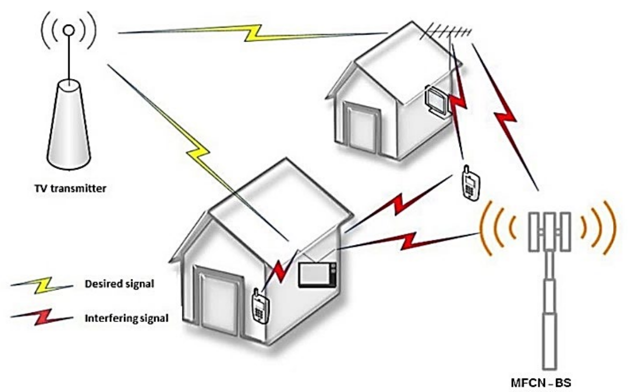

Fig. 8. Interference from MFCN over terrestrial television receivers in a general scenario [42].

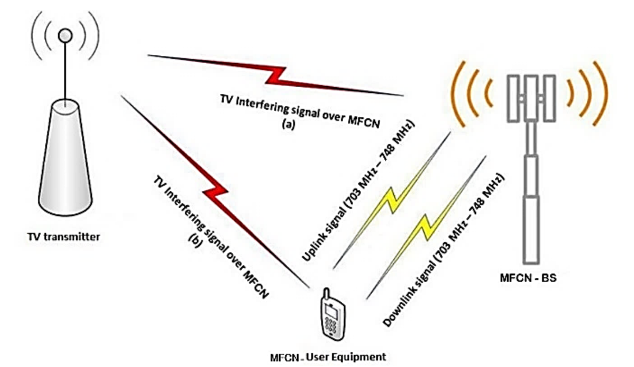

Fig. 9. Interference from terrestrial television over MFCN receivers in a general scenario [42].

B. *Methodology for interference assessment*

Field measurement is conducted to evaluate the mutual interference between the terrestrial television system and MFCN in each examined scenario. After collecting the accurate data, the quality of the received digital TV signal is evaluated using the Subjective Failure Point (SFP) criterion based on ITU regulations [43, 44]. Moreover, there are various indications of interference in digital TV reception, such as pixelation, macro blocking, distorted image, blue/black Screen, freezing video, audio dropouts, and others. On the other side, the initial indicators of interference in MFCN are client complaints (e.g., calls drop, poor sound quality, slow data connection, etc.), and the analytical parameters offered by the base stations (e.g., poor Signal-to-Noise Ratio (SNR), or high Received Signal Strength Indication (RSSI)).

C. *Review of related works*

The article in [45] described step by step how to perform field measurements to investigate the coexistence of DTTV and MFCN in the UHF broadcasting band. The authors also provided key guidelines for obtaining accurate and reliable results by field measurements and how could be used with other coexistence methodologies.

Field measurements were employed in addition to computer simulations or laboratory observations in several of the research described above [10, 28, 34, 40]. The primary goal of field measurements in Brazil [10] was to collect genuine and reliable results in order to verify the efficacy of the SEAMCAT software for analyzing mutual interference scenarios between the digital terrestrial television system and LTE networks operating in the 700 MHz frequency range. Field measurements were performed in Indonesia to determine the range of protection ratios when other devices used the TV white spaces [28]. The field measurement findings were compared to the simulation results, which were quite close, indicating that the simulation may be used as a reference to obtain reliable results. The purpose of the field experiments in Portugal [34] was to validate the practical efficiency of a microstrip-based RF band stop filter in mitigating LTE interference on digital terrestrial TV reception in a real-world interference scenario. In Spain [40], the viability of employing TV white spaces by internal LTE-A femtocells in the rooftop digital TV reception was field-verified. To allow participation in the digital television spectrum, the maximum allowed Effective Isotropic Radiated Power (EIRP) limitations of LTE-A femtocells have been determined.

The researchers in [42] characterized and experimentally analyzed most of the mutual interference scenarios between terrestrial television systems (National Television System Committee (NTSC)/Integrated Services Digital Broadcasting -Terrestrial Broadcasting (ISDB-TB)) and the LTE system operating at the 700 MHz band. The interference scenarios were evaluated using professional equipment based on ITU guidelines. According to the results, the influence of the LTE UE signal critical interference was observed on the terrestrial TV receiver with an indoor antenna. In this scenario, using a narrow-bandwidth filter to mitigate the interference did not work because the UE signal is within the filter's passband. In the case of terrestrial TV interference with the LTE uplink, a drop in the uplink data rate was also detected.

V. CONCLUSION

In this article, we presented a survey on electromagnetic compatibility research between terrestrial television systems and MFCN in the 700/800 bands. We arranged our review of relevant literature according to the approach followed in each research.

Firstly, we described how to utilize statistical modelling and computer simulations to study coexistence for terrestrial television systems and MFCN and reviewed related literature. We found that simulations and theoretical studies were extensively utilized in coexistence investigations since they are a cost-effective method to conduct many experiments. SEAMCAT is the most utilized simulation tool in research studies that adopt statistical modeling and computer simulations to assess interference between terrestrial television systems and MFCN in co-channel and adjacent channels. SEAMCAT enables simulating various scenarios that would be difficult to perform using field measurements. The authors examined the impact of the distance between interfering systems, protection range, transmission power, the number of interferers, and other variables on interference scenarios. Most simulation studies concluded that minimum protection distances and guard bands should be maintained to ensure electromagnetic compatibility between the two systems. However, simulation is limited by simplifying assumptions that may differ significantly from the real performance of the transmitter or receiver, resulting in only directionally accurate outcomes. Measurements should be performed to offer a more thorough and accurate assessment of coexistence.

Afterward, we explained how to emulate the coexistence scenarios in the laboratory and discussed the associated research studies. Laboratory measurements are utilized to determine receiver performance and behavior in a regulated environment allowing for a high level of automation. Mutual interference scenarios have been emulated, considering the impacts of MFCN signal characteristics such as different bandwidths, various traffic loads, and modulation schemes. Protection ratio measurements and link budget analysis were utilized to investigate interference scenarios. Most studies that followed the laboratory measurements approach recommended high-quality standards for the considered scenario to ensure the electromagnetic compatibility of both systems, as well as the necessity of using a low-pass filter to reduce MFCN interference in terrestrial TV channels. Although outcomes of the laboratory measurements also yield realistic simulation parameters based on real equipment performance, they do not replace additional validation in the real-world working environment.

Lastly, we described how to implement field measurements scenarios to evaluate interference, as well as a review of the literature that used an experimental approach. Field measurements provide validating the results of simulations and laboratory work, as well as the detection of factors that influence coexistence performance in practical operating conditions. Based on relevant reference studies, the field validation revealed the following conclusions: 1) The effectiveness of the SEAMCAT simulation tool, with simulated results that were quite close to the measured values. 2) The feasibility of employing TV white spaces by other services, but with the obligation to determine the range of protection ratios. 3) The practical efficiency of a low-pass filter in mitigating MFCN signal interference into digital TV channels in most scenarios, except for MFCN-UE interference on a terrestrial TV receiver with an internal antenna, where the filter failed because the UE signal is within the filter's pass range. The primary limitations of field measurements are cost inefficiency and time-consuming to conduct. On the other hand, the limited statistical foundation of field measurement campaigns prevents drawing significant conclusions.

Ultimately, the fundamental goal of the described coexistence studies was to guarantee radioprotection against harmful interference that occurs between terrestrial television systems and MFCN in digital dividend bands. In the long term, wireless coexistence studies and 5G technologies advances will contribute to the creation and development of a converged ecosystem that utilizes spectrum resources efficiently and ensures the harmonic coexistence of radio systems.

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