Frequency and Network Planning and Optimization of the Digital Terrestrial Television DVB-T2 Networks in Colombia

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Abstract

In December 2011, Colombia updated its national Digital Terrestrial Television (DTT) standard from DVB-T to DVB-T2, the second-generation European DTT standard. DVB-T2 is the current state-of-the art DTT system in the world, and it brings very significant improvements in terms of capacity, robustness and flexibility compared with any other DTT technology. The iTEAM Research Institute was very involved in the promotion and adoption of DVB-T2 in Colombia. The case of Colombia is unique because it was the first country to deploy DVB-T2 with 6 MHz channelization, and because the digital networks will co-exist with the analogue NTSC network until the analogue switch-off and with digital ISDB-Tb and DVB-T networks in the neighbor countries. Furthermore, DVB-T2 networks will be deployed from scratch without any constraint imposed by existing DVB-T infrastructure. This paper provides an overview of the frequency and network DVB-T2 planning activities performed by the iTEAM Research Institute in cooperation with the Spectrum Regulator of Colombia.

Keywords: 4G LTE; analogue switch-off; digital dividend; digital terrestrial television; DVB-T; DVB-T2, ISDB-Tb, frequency planning; network planning; NTSC; single frequency networks.

1. Introduction

DVB-T2 (Digital Video Broadcasting – Terrestrial 2nd generation) is the current state-of-the art Digital Terrestrial Television (DTT) system [1]. It was designed with the aim of offering multi-channel broadcasting of High-Definition (HD) TV, optimizing the robustness, capacity and quality of service compared with first-generation DTT standards. It provides a throughput close to theoretical channel capacity and outperforms previous standards offering at least 50% more efficiency [2]. Today, commercial DVB-T2 services are on air in twenty six countries worldwide including Europe, Asia and Africa. In America, Colombia is the only country that has adopted DVB-T2.

Colombia initially adopted in 2010 DVB-T (Terrestrial) as the national DTT standard with MPEG-4 video coding [3]. However, taking advantage of the fact that the networks were not yet deployed, at the end of 2011 it was decided to update the technology to DVB-T2 due to the great technical improvements and new business opportunities offered. The iTEAM Research Institute, member of the European digital television standardization forum DVB since 2010, was very involved in the promotion and adoption of DVB-T2 in Colombia giving seminars about DVB-T2 to the national regulators, broadcasters, engineer associations and universities.

The strategy adopted in countries which already had deployed DVB-T networks (e.g. UK or Sweden) was to keep the network design and coverage level and maximize the transmission capacity. In Colombia it was shown that DVB-T2 could offer 70.26% more transmission capacity than DVB-T, but this constraint does not apply, and hence new possibilities arise to exploit the potential of DVB-T2. However, the update of the DTT network designs to DVB-T2 in Colombia requires a detailed study in order to maximize the benefits of this new technology.

The particular case of Colombia is very special, because it was the first country to use DVB-T2 with 6 MHz chan-

The Mobile Communications Group of iTEAM has been involved in the promotion and adoption of DVB-T2 in Colombia, and since the second half of 2012, it has been working with the spectrum regulator on the frequency planning and optimization of the DVB-T2 networks.

nelization. Furthermore, DVB-T2 has to co-exist with the analogue NTSC (National Television System Committee) technology until the analogue switch-off, scheduled in December 2019; and with the Brazilian version of the Japanese DTT standard ISDB-Tb (Integrated Services Digital Broadcasting – Terrestrial) in the neighboring countries. Other particularities of Colombia are that the digital dividend of the 700 MHz band took place before the digital transmissions started, and that the public and the private operators will deploy different networks and they will operate in adjacent channels. In Colombia there are two national analogue TV networks, each one with more than 200 stations spread across the whole country using a nominal output power of transmitter ranging from 20 W to 5 kW. One network is used for the public broadcaster, Radio Televisión de Colombia (RTVC), to offer three TV services, and the other one used for the private broadcasters, Caracol TV and RCN, which emit two TV services. Additionally to the national broadcasters, there are 8 regional and 43 local broadcasters. Thanks to the robustness of digital television signal against analogue television, these two networks could operate at adjacent frequency channels.

This paper provides an overview of the frequency and network DVB-T2 planning activities performed by the iTEAM Research Institute in cooperation with the Spectrum Regulator of Colombia ANE (Agencia Nacional del Espectro), including:

1. Co-existence of digital DVB-T2 networks with analogue NTSC networks during the simulcast phase.
2. Co-existence of the two digital DVB-T2 national networks (public and private) which will operate in adjacent frequency channels.
3. Co-existence of the DTT networks with the DTT networks in neighboring countries.
4. Co-existence of DTT networks with cellular 4G LTE networks in the 700 MHz band.
5. Co-existence of DTT networks with the police P25 networks in the 450 MHz band.
6. DVB-T2 Single Frequency Network (SFN) planning and optimization.
7. DVB-T2 frequency planning for the simulcast phase.
8. Analogue switch-off timeline.
9. DVB-T2 frequency re-farming after the analogue switch-off.

The coverage analyses presented in this paper has been obtained using high resolution cartography such as Digital Terrain Maps (DTM), digital buildings maps and clutter layers.

The rest of the paper is structured as follows. First, a technical comparison between DVB-T and DVB-T2 is presented in Section II. Secondly, an overview of the different co-existence studies performed for the digital DVB-T2 networks is presented in Section III. Section IV is devoted to the network and frequency planning studies. Finally, the paper is concluded in Section V.

2. An Overview of DVB-T2

DVB-T2 offers a wide range of transmission modes, making it a very flexible standard. The main differences between the transmission modes of DVB-T and DVB-T2 are presented in Table 1. DVB-T2 includes significant technical innovations, such as the latest-generation Forward Error Correction (FEC), higher order constellation (256QAM), increase in the number of OFDM carriers (16K and 32K) with optional bandwidth extension, new Guard Interval (GI) fractions, and scattered Pilot Pattern (PP) optimization according to the GI; but it also includes new functionalities such as multiple Physical Layer Pipes (PLPs), time interleaver, rotated constellations, Multi-Input Single-Output (MISO) Alamouti transmission mode, Peak-to-Average Power Ratio (PAPR) mechanisms, Future Extension Frames (FEFs), Generic Stream Encapsulation (GSE), and a mobile profile known as T2-Lite.

Parameter	DVB-T	DVB-T2
FEC Scheme and Coding Rates	CC+RS 1/2, 2/3, 3/4, 5/6,7/8	LDPC+BCH 1/2, 3/5, 2/3, 3/4, 4/5, 5/6
Modulations	4QAM, 16QAM, 64QAM	4QAM, 16QAM, 64QAM, 256QAM (rotated optional)
FFT size	2K, 8K	1K, 2K, 4K, 8K, 16K, 32K
Guard Interval	1/4, 1/8, 1/16, 1/32	1/4, 19/128, 1/8, 19/256, 1/16, 1/32, 1/128
Scattered Pilots	8% of total	1%,2%,4%, 8% of total
Maximum Capacity @ 6MHz	23.8 Mbps	37.0 Mbps

Table 1. DVB-T vs. DVB-T2 transmission mode comparison.

Multiple PLPs allow service-specific robustness within a single frequency channel to meet different reception conditions (e.g. indoor or roof-top antenna). Time interleaving provides further signal robustness against impulsive noise and Doppler. Rotated constellations improve the robustness against loss of data cells by ensuring that loss of information from one channel component can be recovered in another channel component. The MISO Alamouti technique introduces a signal decorrelation for each group of transmitters, such that the SFN gain is maximized. Tone Reservation (TR) and Active Constellation Extension (ACE) are two optional PAPR reduction techniques which result in a better efficiency of high power amplifiers. GSE allows more efficient Internet Protocol (IP) delivery than Transport Stream (TS). By means of FEFs, DVB-T2 allows the transmission of other technologies in the same frequency channel in a time division multiplex. T2-Lite is a mobile profile included in the release 1.3.1 of the DVB-T2 standard to improve the coexistence of fixed and mobile services while reducing the complexity of mobile receivers [4].

The technical innovations and the new functionalities included in DVB-T2 bring very significant improvements in terms of coverage, capacity, SFN distance and flexibility compared with any other DTT technology:

2.1. Coverage Gain

The FEC coding of DVB-T2 is at the cutting edge of coded modulation technologies. The adopted LDPC (Low Density Parity Check) codes perform very close to the theoretical limit, with a gap to Shannon capacity lower than 1dB in Gaussian channels. Compared to the Convolutional Coding (CC) employed in DVB-T, the achieved gain ranges from 2.3 dB of Carrier-to-Noise Ratio (CNR) for low bit rate services to more than 3.2 dB for high bit rate services in stationary channels [5]. Depending on the network topology and geographical conditions, it means more than doubling the coverage area. The FEC gain is higher in mobile channels, but DVB-T2 also introduces a time interleaver which significantly improves the robustness of the transmission for mobile services, achieving an overall gain in the order of 9 dB in high velocity scenarios (i.e. 144 km/h) [4].

Rotated constellations also provide additional robustness, especially for low-order constellations and high coding rates. The actual gain depends on the channel too, ranging from 0.5 to 2 dB, but for high-order modulations (64QAM and 256QAM) the gain is negligible. The SFN gain offered by MISO Alamouti can be up to 2.5 dB when the power and delay differences between the signals are negligible [6].

2.2. Capacity Gain

All in all, the potential capacity gain of DVB-T2 compared to DVB-T can reach up to 70% [6]. The use of 256-QAM increases the spectral efficiency to 8 bits per symbol, 33% more compared to the highest modulation order of DVB-T, 64-QAM. The improved performance of the FEC coding can also be translated into a capacity gain, being possible to use for a given CNR requirement a modulation and coding rate with a higher spectral efficiency. Basically, it is possible to increase one modulation order and keep the same coverage.

The new larger FFTs of 16K and 32K also increase the system capacity for a given SFN distance at the expense of a reduced mobility performance because it is possible to reduce the GI overhead. Larger FFT sizes imply longer useful symbol time durations, which allows reducing the GI fraction for a given guard interval time duration. Furthermore, for these FFT sizes it is possible to employ more sub-carriers due the steeper out of band attenuation of the spectrum (this is known as extended bandwidth modes), which represents an additional capacity gain of roughly 2%. On the other side, the mobility performance is decreased because the frequency separation between sub-carriers is reduced, which increases the vulnerability to the Doppler Effect. The maximum supported speed is approximately reduced by half when doubling the number of sub-carriers.

The overhead due to channel sampling is also reduced in DVB-T2 by means of multiple PPs. While DVB-T employs a single dense PP with 10.6% overhead, DVB-T2 defines eight different patterns with an overhead ranging from 10.6% down to 1.35%. This allows minimizing the pilot overhead according to the target reception scenario.

2.3. SFN Distance Gain

The basic parameter that defines the size of the SFN area is the guard interval time duration, Tg, which depends on the FFT size and the GI fraction. Signals arriving from transmitters with a relative delay higher than the GI duration generate Inter Symbol Interference (ISI). The max-

FFT size	Guard Interval (GI)						
	1/128	1/32	1/16	19/256	1/8	19/128	1/4
32K	11,2	44,8	89,6	106,4	179,2	212,8	n/a
16K	5,6	22,4	44,8	53,2	89,6	106,4	179,2
8K	2,8	11,2	22,4	26,6	44,8	53,2	89,6
4K	n/a	5,6	11,2	n/a	22,4	n/a	44,8
2K	n/a	2,8	5,6	n/a	11,2	n/a	22,4
1K	n/a	n/a	2,8	n/a	5,6	n/a	11,2

Table 2. Maximum SFN distance (km) between transmitters at 6 MHz.

The case of Colombia is very special because it is the first country to deploy DVB-T2 with 6 MHz channelization and it will be deployed from scratch without any constraint imposed by existing DTT infrastructure. DVB-T2 will have also to co-exist for the first time with analogue NTSC and digital ISDB-Tb transmissions.

imum GI duration in DVB-T for 6 MHz bandwidth is 298 μs, and it is given by the FFT 8K GI 1/4 mode [5]. This corresponds to a maximum cell radius of about 89 km. In DVB-T2, the new large FFT sizes (16K and 32K) allow larger SFN distances between transmitters at the expense of a reduced mobility performance. DVB-T2 allows a cell radius of up to 212 km for 6 MHz bandwidth (FFT 32K, GI 19/128, Tg 532 μs). Table 2 summarizes the maximum SFN distance (km) as a function of FFT size and GI for 6 MHz bandwidth.

3. Coexistence Studies

In this section, results obtained for the coexistence studies between DVB-T2 and other communication and television systems in Colombia are presented. As mentioned in the introduction, DVB-T2 should coexist in the UHF band with DVB-T2, NTSC, 4G LTE, and P25 networks. The frequency allocation in this band for all these services is shown Figure 1.

To evaluate the coexistence between two signals, the first step consists on measuring the interference protection ratios (PR) for each signal with respect to the other. A PR is the minimum value of the difference between the useful and interfering signals, expressed usually in dB, required at the receiver input to accomplish with a particular quality requirement. The lower the PR (even negative), the more interfering signal level is allowed and hence, the lower the interferences issues in a real scenario. The measurement of all possible PRs was performed in the Mobile Communications Laboratory of iTEAM, which account with many facilities to generate, receive and evaluate signals of multiple DTT standards (DVB-T/T2/NGH/S, NTSC, PAL, ISDB-T), as well as many mobile communications standards (TETRA, P25, LTE-UL, LTE-DL, GSM). Wanted and interfering signals were generated independently, mixed to emulate the interference, and evaluated on the receiver.

Once the PRs have been obtained, the second step consisted in evaluating the coexistence in a real scenario. To accomplish this, the link budget is computed by taking into account transmission and reception parameters of the wanted signal. The results of the link budget can be confirmed by performing software interference simulations in real scenarios where the real terrain model is taken into account.

3.1. Coexistence of the Digital and the Analogue Terrestrial TV Networks

In Colombia, digital and analogue TV emissions will coexist until the analogue switch-off in 2019, it will be the first time that the analogue standard NTSC and the digital standard DVB-T2 coexist. The most critical situation is when NTSC is interfered by DVB-T2 signal since the robustness of analogue signals is very poor compared to digital signals.

The measured protection ratios obtained in laboratory for the public broadcaster configuration (MOD 64QAM, COD 2/3, PP3, FFT 16KE, GI 1/8, Bitrate 19.33 Mbps) are shown in Table 3. Other DVB-T2 modes and different transmission techniques were evaluated. The protection ratios were measured following ITU-R BT.2215-2 recommendation [7].

Channel	N-2	N-1	N	N+1	N+2
DVB-T2 (dB)	-39	-28	-3	-28	-39
NTSC (dB)	-23	-2	38	0	-23

Table 3. Interference protection ratios for digital DVB-T2 signals interfered by analogue NTSC signals and vice versa.

From the results shown in the table, it can be concluded that if two transmitters are co-located, the transmit power of the digital signal cannot be higher than the transmission power of the analogue signal. If higher power for the digital signal is required, the use of a guard channel is necessary. As an illustrative example of the interference studies performed using simulations, Figure 2 shows the effect of using digital power transmission higher than analogue power transmission.

3.2. Coexistence of the two national DVB-T2 Networks

Thanks to the robustness of digital television signal against analogue television, the protection ratios between two digital channels are less restrictive, so the assignment of adjacent frequencies is allowed. To ensure the coexistence of the two nationwide DVB-T2 networks in adjacent frequency channels, protection ratios for the public broadcaster configuration and the private broadcasters (MOD 64QAM, COD 3/4, PP2, FFT 16KE, GI 1/8,

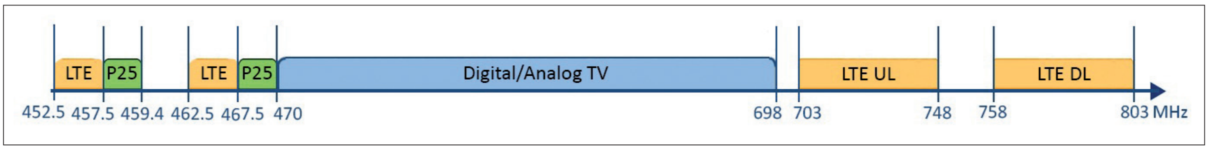
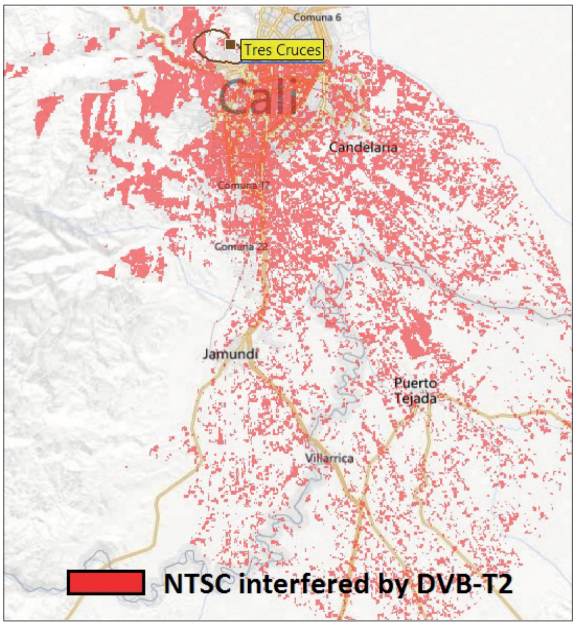


Figure 1. Channelization of Colombia in the digital/analogue TV range.



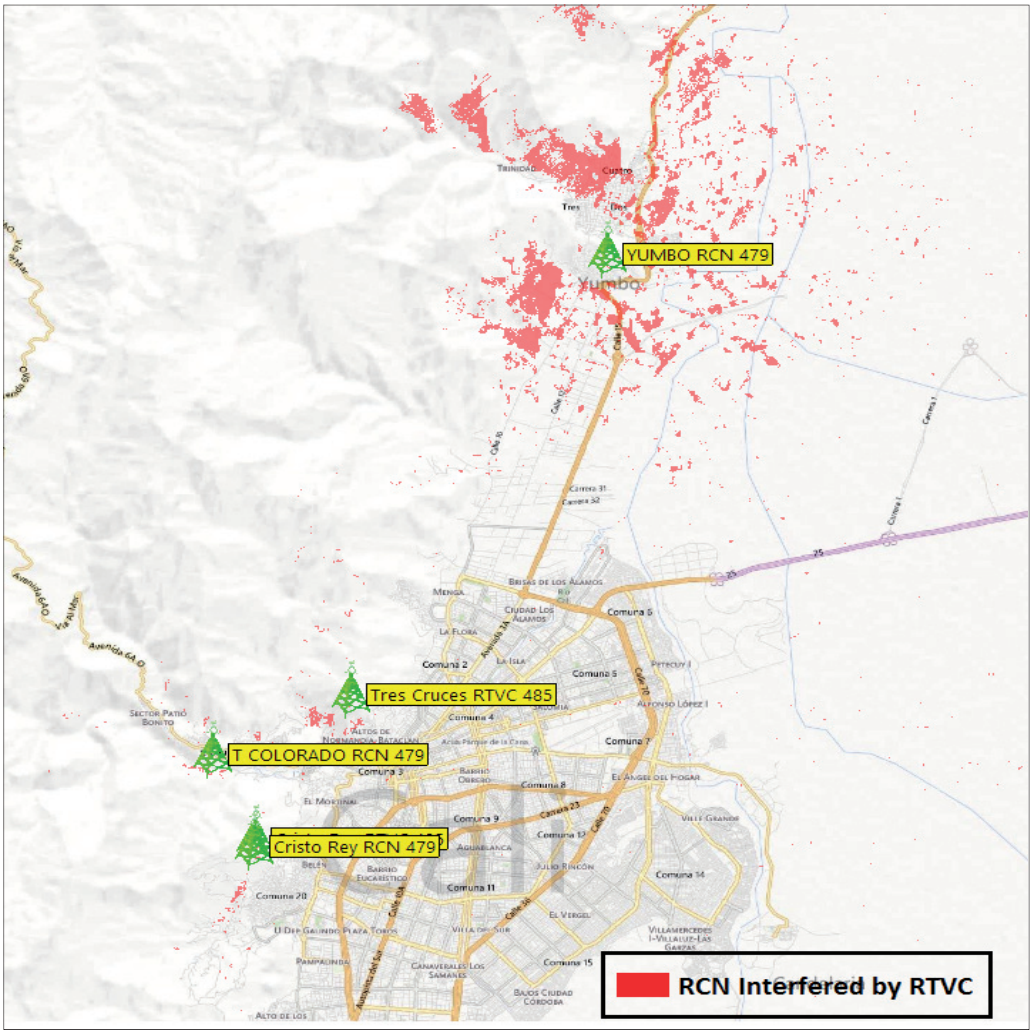
■ **Figure 2.** Adjacent channel (N+1) interference for analogue NTSC signal interfered by a digital DVB-T2 signal (red) with DVB-T2 transmit power twice (3 dB) that analogue NTSC signal.

Bitrate 20.92 Mbps) configurations were measured, see Table 4. The private configuration mode is sturdier compare with public mode, but offer less transmission capacity.

Channel	N	N±1	N±2
Public mode (dB)	16	-39	-45
Private mode (dB)	15	-39	-45

■ **Table 4.** Protection ratios for digital DVB-T2 wanted signal interfered with by digital DVB-T2 signal.

Using coverage simulations, potential interfered zones when operating in adjacent channels were identified. In general, the adjacent channel interference appears in places where the transmitters of the two networks are not co-located. Figure 3 shows an example is the surroundings of the city of Cali. The solution was to avoid adjacency depending on spectrum occupancy. The co-localized transmitters are less critical unless that transmission powers are too unbalanced. Thus, to evaluate the coexistence between two different digital signals, the power supplied from each transmitter and their locations



■ **Figure 3.** Adjacent channel (N+1) interference (red) between public broadcaster network (wanted signal) and private broadcaster network (unwanted signal).

must be taken into account. If the transmitters are co-located and radiate equal powers, they will be able to co-exist if they commit with the spectral emission mask (critical or non-critical). If they radiate with different power (in co-location or no co-location cases) the protection ratios should be checked.

The studies showed that, after delay optimization and accomplishment of protection ratios presented in this document, the interference (red) between public broadcaster network (wanted signal) and private broadcaster network (unwanted signal) is around 1% for the two big SFNs working at adjacent channels.

3.3. Coexistence with DTT Networks in Neighbor Countries

In Colombia, DVB-T2 will co-exist with ISDB-Tb (in Brazil, Ecuador, Peru and Venezuela) and with DVB-T (in Panama). Currently, Colombia has only analogue TV frequency border agreements with Ecuador, based on an even/odd channel distribution across borders. For the remaining neighbor countries a similar approach is envisaged. However, ISDB-Tb implements a frequency offset from the central carrier of 1/7 MHz (142.857 kHz), which leads to asymmetrical protection ratios, and an even/odd channel distribution implies a more demanding frequency planning.

In the case of Venezuela border our results show that a two zones distribution will leads to more efficiently distribution, In that way each country will use even channels in one zones and odd channels in the other zone.

The protection ratios that ensure coexistence between Colombian public broadcaster and Brazilian broadcasters (MOD 64QAM, COD 3/4, FFT 8K, GI 1/8, Bitrate 18.25 Mbps) are shown in Table 5. It can be seen that DVB-T2 provide higher capacity (20.48 Mbps) for the same MODCOD and FFT size, also DVB-T2 is more robust against interferences than ISDB-Tb. This means that a frequency used by a neighbor country can be re-used closer from the border in Colombia.

Channel	N-2	N-1	N	N+1	N+2
PR DVB-T2 (dB)	-45	-38	14	-41	-45
PR ISDB-T (dB)	-34	-27	20	-25	-27

Table 5. Protection ratios for digital ISDB-Tb signal (Brazilian mode) and digital DVB-T2 signal (Colombian public broadcaster mode).

In Figure 4 the adjacent channel interferences for DVB-T2 (channel 16) interfered with by ISDB-T (channel 15) and vice versa are shown.

3.4. Coexistence Studies of DVB-T2 and 4G LTE in the Digital Dividend

The digital dividend is the broadcast spectrum released for mobile communications with the arrival of the DTT and the analogue switch-off. However, in Colombia the 700 MHz band has been already allocated to 4G LTE cellular networks before the analogue switch-off. In several countries in Europe, it was observed that 4G LTE cellular networks operating in the 800 MHz band could interfere DTT signals in the two adjacent channels, since current TV tuners are designed to span the complete broadcast spectrum band. In Colombia, LTE is using the Asia-Pacific Telecommunity (APT) channelization, which main difference compared to the channelization used in Europe is that the uplink (UL) is located in the lower part, instead

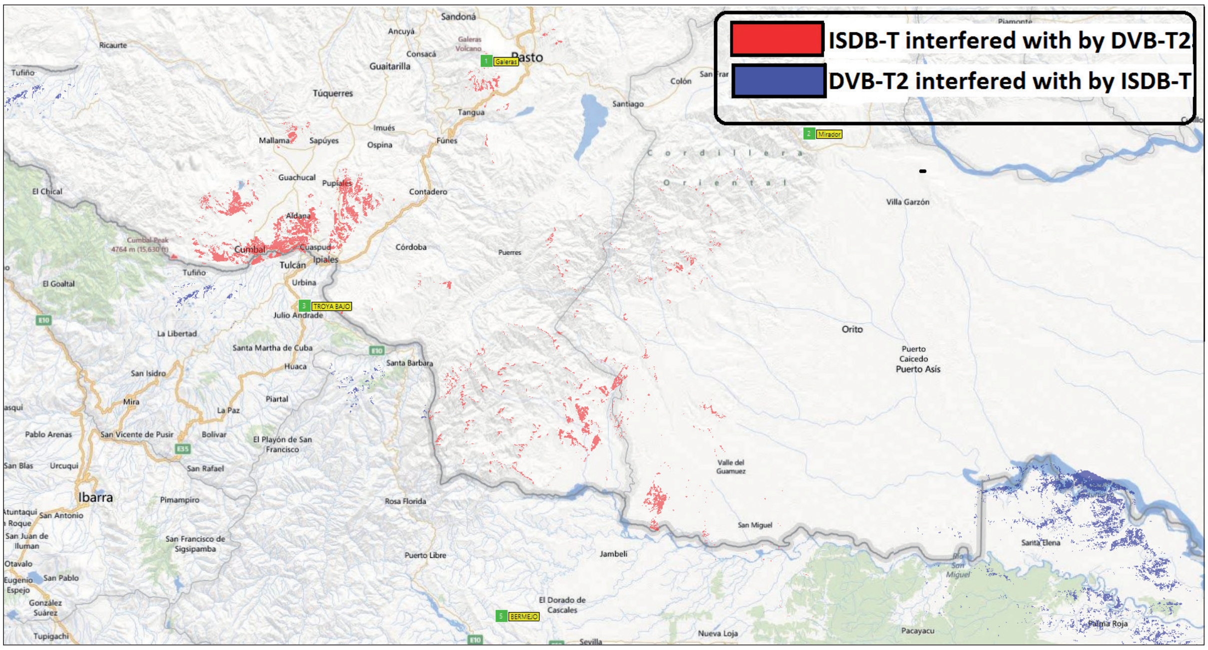
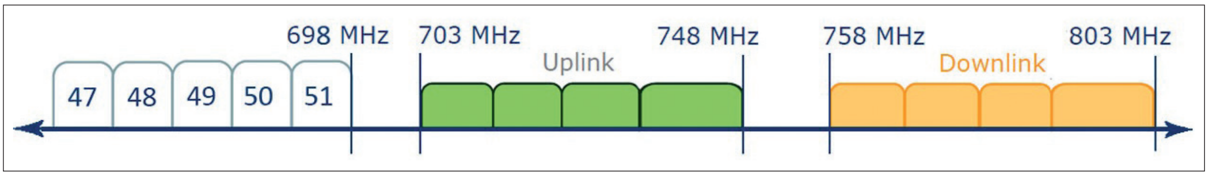


Figure 4. Adjacent channel (N+1) interference at Ecuador Colombia Border.

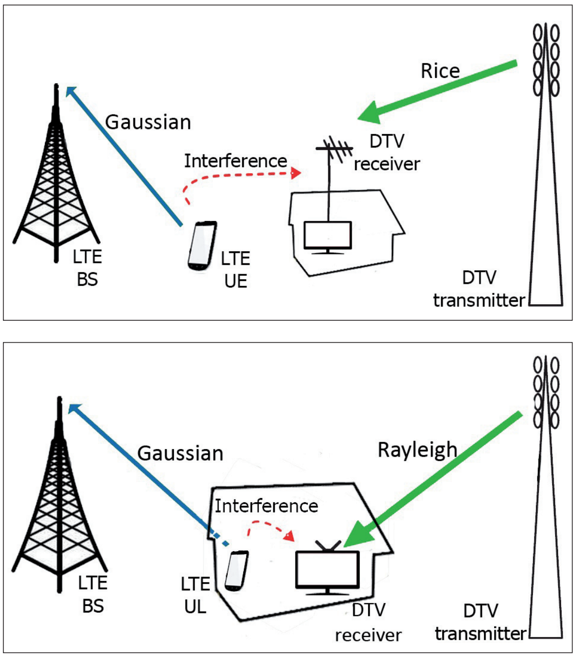


■ **Figure 5.** LTE and DTT communications allocation in Colombia.

of the downlink (DL), see Figure 5. The fact of having the LTE UL in the lower part of the band considerably complicates the interference issue, especially for indoor DTT reception, even though there is a guard band of 5 MHz (in Europe the guard band is only 1 MHz).

Scenarios were classified according to: the type of LTE interfering link adjacent to DTT: UL or DL; the DTT reception type: portable indoor or fixed outdoor; and the position of the LTE cellular phone (User Equipment, UE): inside or outside the building. Two worst-case scenarios were identified, as shown in Figure 6:

- Scenario 1: LTE-UL interfering fixed rooftop DTT reception with the UE outside the building.
- Scenario 2: LTE-UL interfering portable indoor DTT reception with the UE inside the building in the same room of the DTT receiver.



■ **Figure 6.** Critical scenarios for LTE-UL interference: fixed (left) and portable indoor (right) DTT reception.

These scenarios were directly related with both different types of reception in Colombia, i.e., rural fixed and urban indoor DTT reception. For fixed rooftop DTT reception, the worst case is when the UE is in Line-of-Sight (LoS) with the DTT antenna at the distance that maximizes the interference. Obviously, if the UE is inside the building the interfering signals will experience an additional penetration loss. The same idea applies for portable indoor DTT reception scenarios, where the UE is in a different room than the DTT receiver or outside the building. For both scenarios, the worst case is when the DTT receiver is just at the coverage edge, receiving the minimum required DTT signal power, and the UE transmits the maximum possible power level (23 dBm).

Regarding the measured interference protection ratios, the impact of the three following LTE parameters was studied:

- Traffic loading: 1 Mbit/s (light loading where only a small number of resource blocks are used for some of the time), 10 Mbit/s (medium loading), or 20 Mbit/s (high loading).
- LTE bandwidth: 5, 10, 15 or 20 MHz.
- LTE interfering link: UL or DL.

The variation of these parameters was studied for a certain range of guard bands, i.e. from 0 to 11 MHz, taking into account all possible PRs for the two adjacent DTT channels (channels 50 and 51). It was observed that:

- LTE-UL generates more interference than LTE-DL, obtaining approximately 10 dB worse PRs.
- When LTE-UL is the adjacent link to DTT, the lower the traffic load, the higher the interference level due to the higher time and frequency variability of the LTE signals.
- With 5 MHz or higher guard bands, a higher LTE bandwidth is more prejudicial. This is due to the difference in occupied bandwidth, which is the 90% of the total, and also the different out-of-band fall for each LTE channelization.
- DTT portable indoor reception is more vulnerable to interference than fixed outdoor reception. For LTE-UL as the interfering link, PRs are 1 dB worse.

The potential solutions to reduce the interferences consist in increasing the guard band by reducing the number of DTT channels or using special filters for DTT receivers. From the results of the project, it was advised not to use channel 51 for the technical plan of television. For channel 50, it was concluded that:

- For fixed outdoor DTT reception, even increasing the guard band to 11 MHz, an extra low-pass filter is also needed, with an out-of-band attenuation of 15 dB for the critical case.
- For portable indoor DTT reception, the minimum distance between the LTE-UE and the DTT receiver to avoid any interference is 5.8 m. With a low-pass fil-

The interference issues between 4G cellular networks and DVB-T2 networks at 450 MHz and 700 MHz (digital dividend) bands were investigated, and interference protection ratios were measured in laboratory conditions and network planning studies were performed.

ter, this distance is reduced to 2.7 m. For typical values of LTE-UE transmit power, the minimum distances without filter are 0.4 m in rural environments and 0.15 m in urban environments (2 dBm and -9 dBm transmit power, respectively). Maximum UE transmission power to avoid any interference is -9 dBm.

If channel 51 were used, critical conditions would get worse:

- For fixed outdoor DTT reception, an extra low-pass filter with an out-of-band attenuation of 19 dB is needed for the critical case. There are two conditions for no requiring a filter: when the LTE transmitted power is lower than 5 dBm, and when the DTT received power is higher than -66 dBm. Rejecting the use of channel 51 as a possible solution and
- For portable indoor DTT reception, the minimum distance is increased to 7.7 m, and 4 m with a low-pass filter (the minimum distances without filter are 0.8 m and 0.25 m for 2 dBm and -9 dBm transmit power).

3.5. Coexistence Studies of DVB-T2 and P25

In Colombia, radio trunking communications known as Project Apco-25 (also called P25) are allocated in the lower part of the UHF band. Thus, P25 transmissions are in the adjacent lower band of DTT band as shown in Figure 7. P25 transmits in analogue, digital or mixed mode with 12.5 kHz channelization using FDMA (Frequency-Division Multiplexing Access).

In Europe, co-existence studies between TETRA (European trunking system with 12.5 kHz channelization) and DVB-T were carried out by the European Conference of Postal and Telecommunications Administrations (CEPT), concluding that the most critical case is when TETRA repeaters BTS are interfered by DTT transmissions [8]. The same problem was found in Colombia, where high-power DVB-T2 transmitters could interfere nearby P25 base stations. This scenario was analyzed in detailed as shown in Figure 8.

Firstly, the protection ratios were measured in laboratory. The PRs for the P25 upper band (the lower band is not so critical since the guard band with DVB-T2 is higher) obtained were 1 dB worse if channels 14 and 15 are transmitted at the same time than for channel 14 transmitting alone. Once the PRs were measured, the coexistence between both technologies was analyzed by means of planning simulations. The worst case was when a DVB-T2 station is located near a P25 base station / repeater. Since P25 BTSs transmit with vertical polarization and DVB-T2 networks transmit with horizontal polarization, an additional improvement of the PRs in 10 dB due to the cross-polar discrimination factor (XPD) was taken into account. Thus, the reduction of the service area can be observed in Figure 10 in red color.

The improvement of the use of mitigation techniques such as the installation of asymmetrical filters (more selective in the lower frequency side) in the DVB-T2 channel 14, or the introduction of low pass filters in the P25 BTS were also studied. The asymmetrical filters reduced considerably the interferences that were completely eliminated with the addition of low-pass filters in P25 base stations since these two mitigation techniques improve jointly the protection ratio in 9 dB.

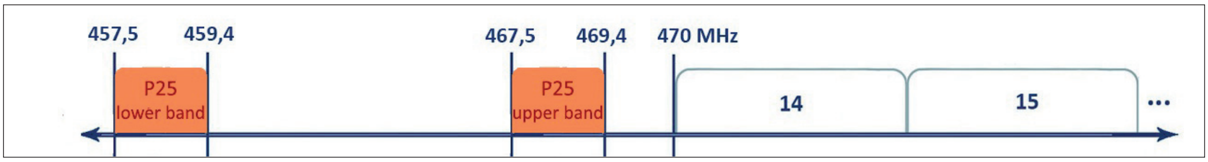


Figure 7. P25 communications allocation in Colombia.

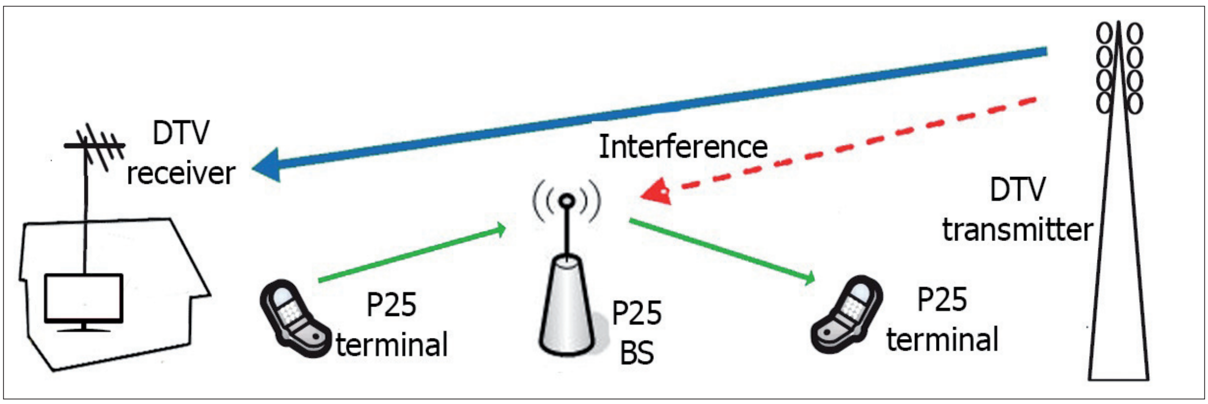


Figure 8. Worst case scenario for interferences of DVB-T2 over P25 communications system.

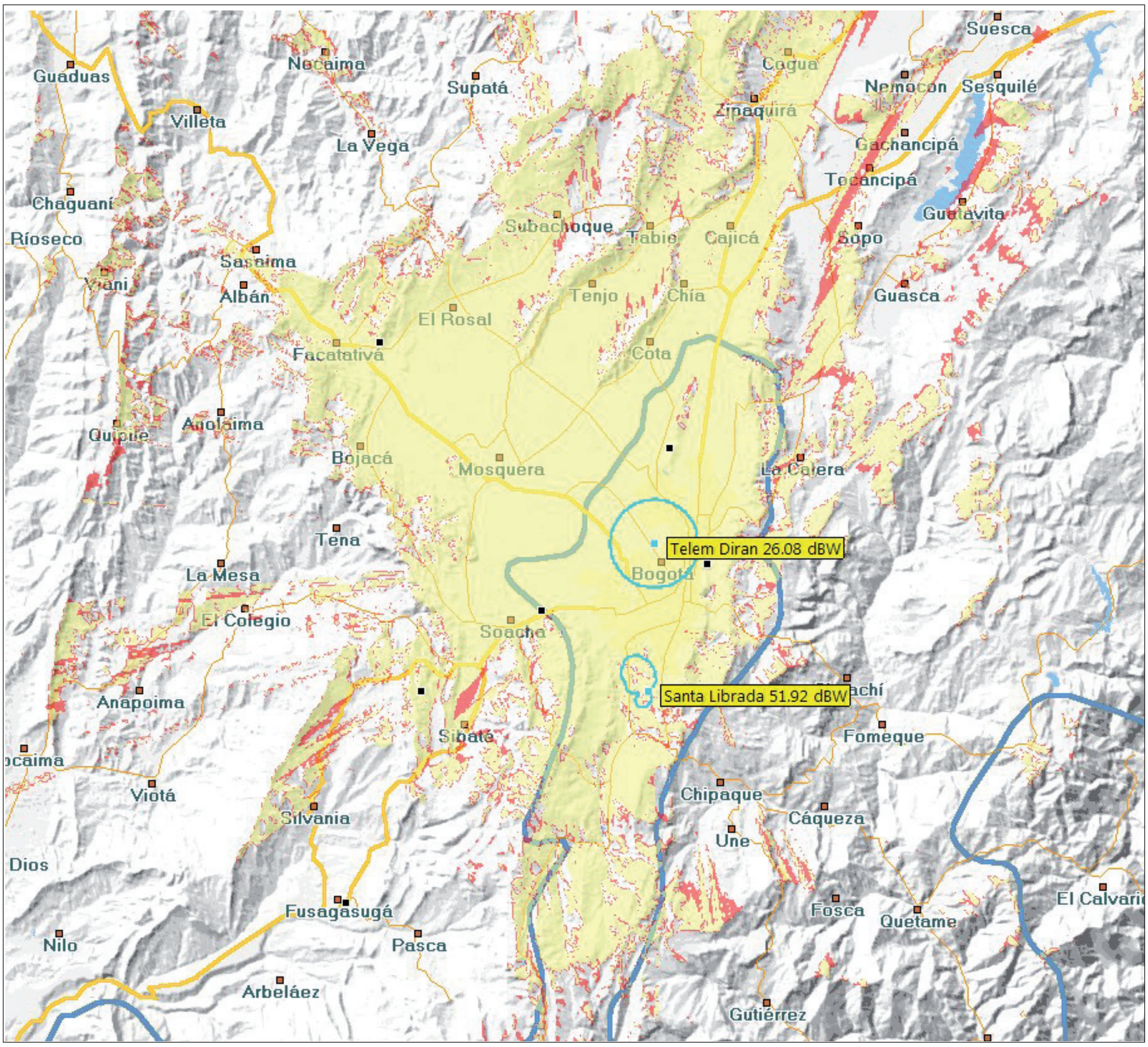


Figure 9. Reduction of the service area of P25 BTS (in red) due to interference from DVB-T2 transmitter without any interference mitigation technique.

4. Network and Frequency Planning

Colombia has currently two national DVB-T2 networks, each with two multiplexes (MUXs). The public network has one MUX for the national TV channels, and another MUX for the regional TV channels (8 in total). The public network has been designed to re-use the existing analogue broadcasting infrastructure as much as possible. In addition, there are 43 analogue local broadcasters that will emit in DVB-T2 too. They are divided in profit or non-profit broadcasters. On the one hand, the local non-profit broadcasters that have the same or near coverage area will be joined in a same MUX with a maximum of five broadcasters per multiplex. On the other hand, the local private broadcasters, have one MUX per each other. Currently, there is only one local private broadcaster, located in Bogotá D.C. Furthermore, in the frequency planning, every capital city of department will have at least two local multiplex reserves.

The frequency planning has to take into account that one more private national broadcasters will work during the simulcast period and one more after the analogue switch-off.

A professional software DTT planning tool has been used with a Digital Terrain Map (DTM) of Colombia with 30 m resolution, a clutter layer with 12 categories, and a municipality layer with 1120 towns and the population projection to 2013 provided by the ANE [9][10].

In cooperation projects with the ANE we evaluated the feasibility of planning national SFNs. It was estimated that Colombia could have the biggest SFN of the world (220 km distance between transmitters), thanks to the new technical features of DVB-T2 and the bandwidth channel of 6 MHz, compared with the 60 km of DVB-T 8 MHz channels (typically in Europe). Additionally, the TV spectrum during the simulcast phase and the repacking after the analogue switch-off was planned, taking into account the digital dividend, the coexistence with analogue/digital networks, the frequency distribution agreements with neighbor countries, etc.

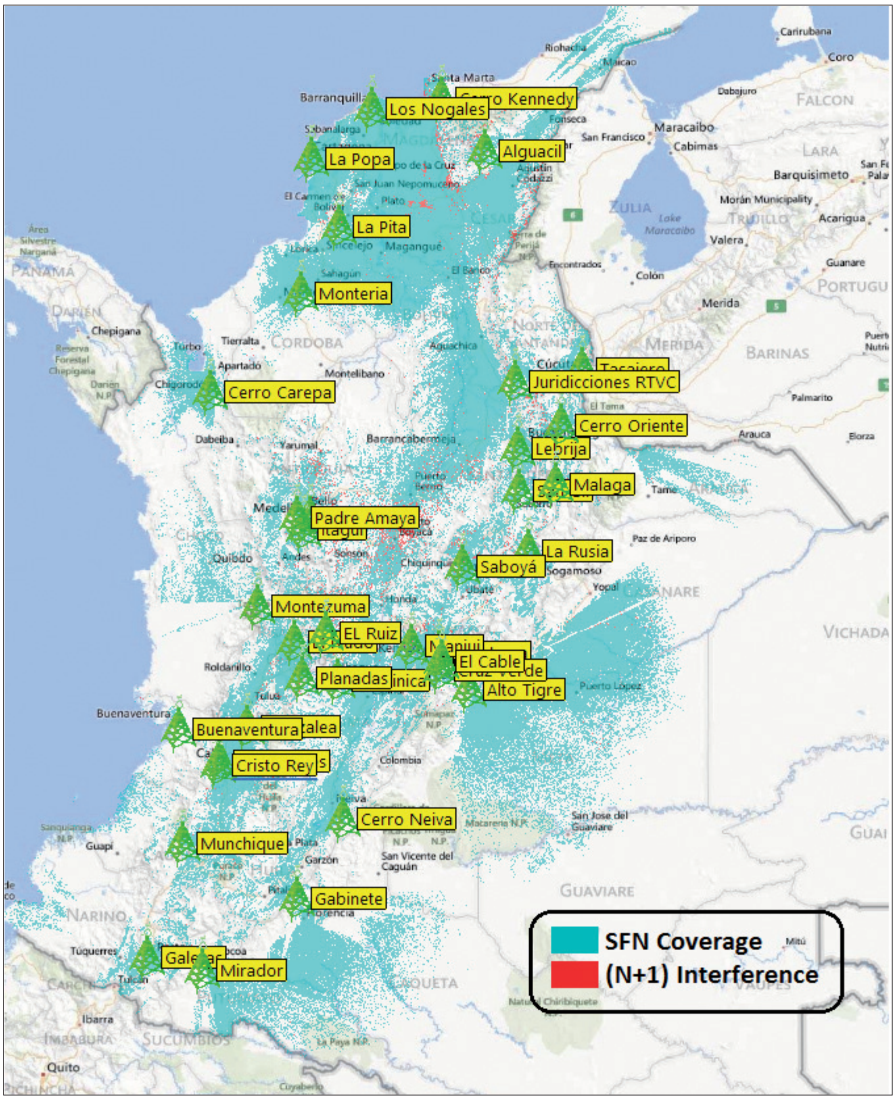
4.1. SFN Network Optimization

The SFN network optimization for Colombia was divided in three stages: selection of suitable DVB-T2 transmission mode, calculation of artificial delays in each transmitter and deployment of low-power transmitter if it was necessary.

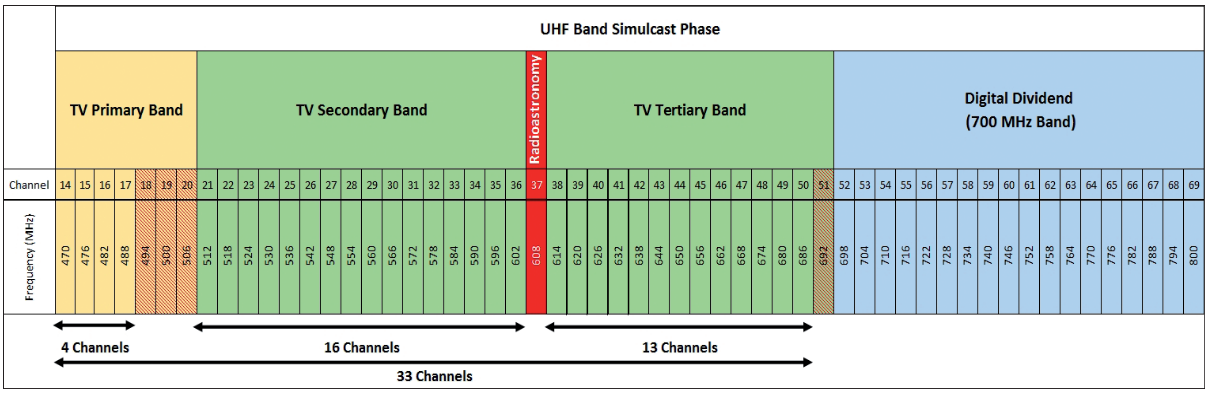
First, different DVB-T2 transmission modes were analyzed and compared with the DVB-T modes initially selected by the broadcasters, in order to identify the best configuration in terms of SFN size, robustness and transmission capacity. To reduce the self-interference in SFN topologies, high FFT modes as 16K or 32K can be selected, which will result in large SFN networks, up to 220 km (FFT 32K, GI 19/128, BW 6MHz) of distance between SFN transmitters, at the expense of penalty in the mobile performance [9][10]. The investigations showed that it is feasible a national SFN covering the whole country instead of requiring three frequencies as the original MFN design for DVB-T with 90 km distance between transmitters. However, it decided the 90 km distance design was kept, trying to maximize the network capacity.

Secondly, with the optimization of the artificial delay of the transmitters, the SFN coverage area was increased. Artificial delay refers to the manually applied delay to the output transmitter signal with the objective to arrive inside the equalization interval. This modification aims at minimizing the areas with self-interference in order to reduce the percentage of interfered population or if it is not possible, move these interferences outside the service area or to locations with a very low population density. The approach followed is based on an iterative search procedure that starts from the maximum relative delay () estimated in the overlapping zones. This value calculates the propagation time of all received contributions at each point of the overlapping areas. Artificial delays in a range of (-,) are assigned iteratively to each transmitter evaluating all possible combinations and estimating the respective SFN self-interference levels until finding the best artificial delays combination.

Thirdly, in those places without coverage either due to a poor signal level or due to SFN self-interferences between transmitters, low power stations can be inserted as gap-fillers.



■ **Figure 10.** Coverage of SFN topology and self-interference of the DTT network of RTVC. Topology formed by the 38 transmitters projected in the first and second phases.

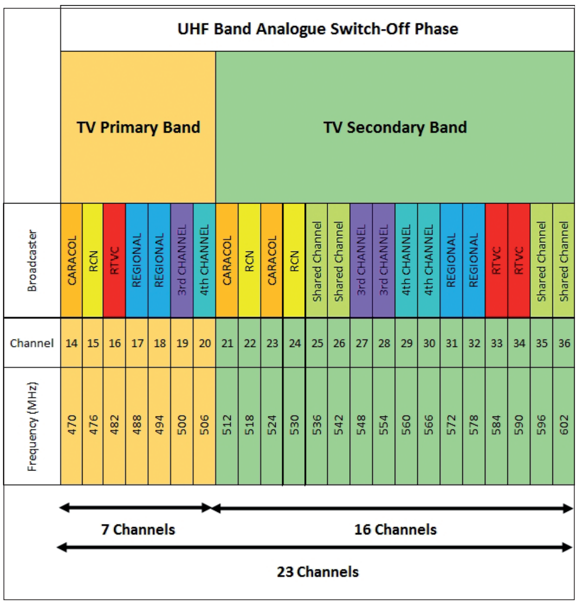


■ **Figure 11.** Frequency availability in Colombia during the simulcast period.

As example, Figure 10 shows the SFN coverage with just only one frequency (light green) and SFN self-interferences (red) of the RTVC primary network. After the optimization of the artificial signal delays at each transmitter, it is possible to reduce the percentage of interfered population due to SFN self-interference down to 0.5%, which could be easily eliminated using low power transmitters.

4.2. Frequency Planning during the Simulcast Phase

Simulcast is the abbreviation for Simultaneous Broadcast. It refers to the period where both analogue and digital broadcast networks coexist. Therefore, the main restriction in this period is the spectrum shortage. In Colombia, this period will last until the end of 2019. As can be seen in Figure 11, a primary band for digital broadcast has been defined from channel 14 to 20. This band is not used in the whole country, except for the channels 18, 19 and 20 that are currently used by military forces and that will be available for DVB-T2 on 2016. The secondary and tertiary bands cover from channel 21 to 36 and from channel 38 to 51 respectively. They will be used during the simulcast phase by both analogue and digital broadcast. Therefore, there are frequencies assigned for analogue transmissions in some places that cannot be used by DTT networks to avoid co-channel and adjacent channel interferences.



■ **Figure 12.** Frequency repacking in Colombia after the analogue switch-off.

Moreover, there are two channels that cannot be used by any broadcasting technology: channel 37 that was assigned for radioastronomy studies by FCC in the USA, with several countries in the Americas that decided to follow suit, and channel 51 that will work as guard channel with the 4G cellular networks in the 700 MHz band. Hence, there are only 33 channels of the UHF band that can be used for DVB-T2. In addition, the frequency borders agreements imply additional restrictions: the odd channels cannot be used in Colombia at the border with Ecuador, Panama, Brazil and Peru. Besides, on the border with Venezuela, Panama and Nicaragua using primary band is forbidden.

One last particular limitation for the Colombian scenario is the necessity of keeping the network topologies of the different broadcasters currently deployed. The private operator has already planned its own network topology, with 188 stations. The public operator has just planned its primary network constituted by 39 stations, so it has been assumed all their current analogue stations will broadcast in digital too.

With these considerations, the proposed solutions have been focused on:

- Maximizing the use of the primary band for 90 km SFN distance. The only parameter to adjust is the artificial delay of the stations.
- Find different SFN frequencies between regions in the secondary band, trying to minimize the interferences with analogue stations.
- Minimize the number of stations that will have to be re-tuned after the analogue switch-off.

As an example, with all these restrictions and considerations, the DVB-T2 network of the public national broadcaster RTVC requires 10 different frequencies, creating small or medium SFN spread in the whole country based on the available spectrum in each area.

4.3. Frequency Repacking after the Analogue Switch-Off

The main activity carried out has been the retuning of the least number of stations allocating all digital networks in the lowest 23 channels of UHF band (between channel 14 and channel 36) and compliance with the border agreements which take effect after the analogue switch-off. This repacking tries to maximize the spectrum efficiency, improving the coverage for TV stations above channel 37 during the simulcast phase, and foreseeing a second digital dividend from channel 38 up to channel 51. A frequency planning for a fourth private national broadcaster has been carried out as well. Another premise considered was the allocation of four all-rounder channels (25, 26, 35 and 36) which can be used by any broadcaster if necessary due to unexpected interferences in the planning phase or due to new stations not yet planned.

Figure 13 depicts the frequency repacking for the RTVC digital network after the analogue switch-off. It can be observed that there will be only 5 frequencies used. The percentage of stations that should be retuned is 20% (48 out of 240 stations).

5. Conclusions

Colombia has updated its national DTT standard to DVB-T2, the world's most advanced system offering more capacity, robustness, and flexibility than any other system, being the first country to deploy it using 6 MHz bandwidth. The iTEAM Research Institute was very involved in the promotion and adoption of DVB-T2 in Colombia, and has been closely working with the spectrum regulator ANE analyzing the co-existence of the digital DVB-T2 networks with analogue NTSC networks during the simulcast phase, with the DTT ISDB-Tb networks in neighboring countries, with cellular 4G LTE networks in the 700 MHz band and the police P25 networks in the 450 MHz band; and optimizing the SFN networks and planning the DVB-T2 frequencies for the simulcast phase and the refarming after the analogue switch-off.

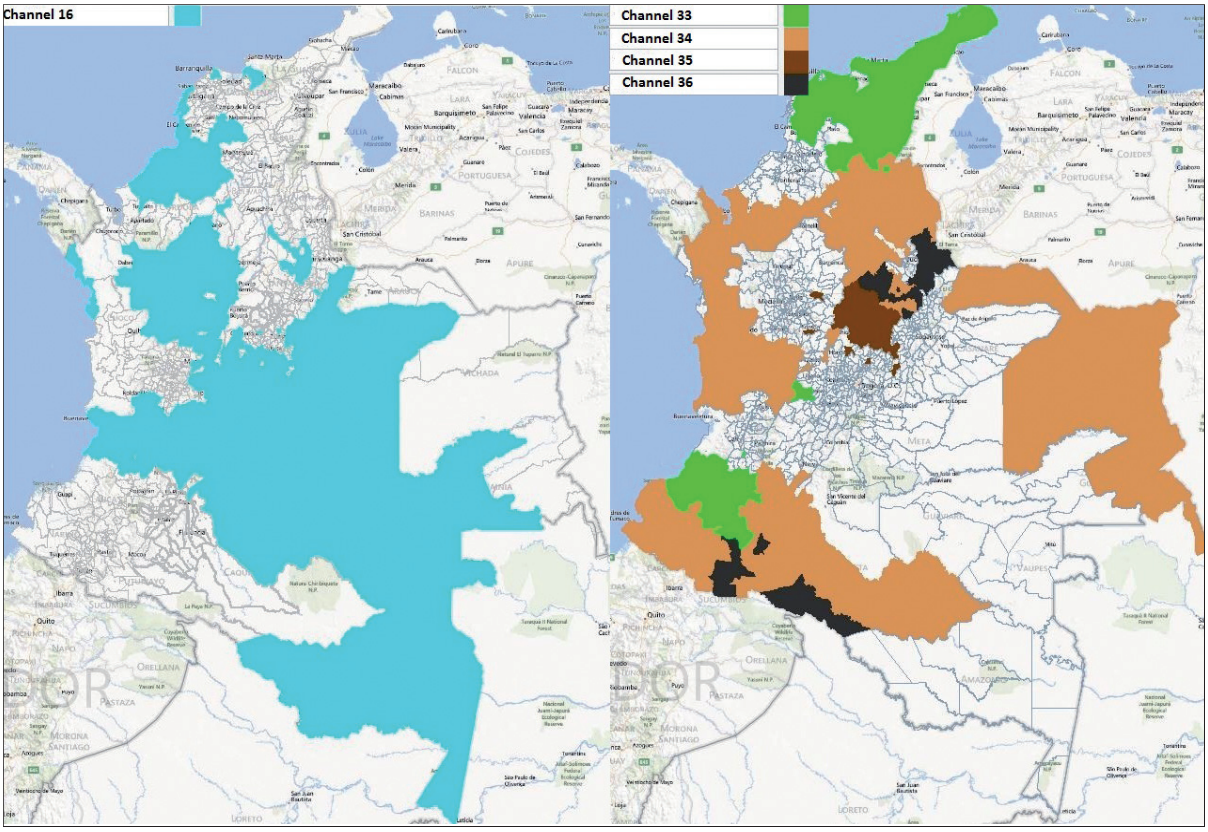


Figure 13. Frequency assignment for the RTVC DVB-T2 network after the analogue switch-off.

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David Gómez-Barquero received the double M.Sc. degree in telecommunications engineering from the Universitat Politècnica de València (UPV), Valencia, Spain, and from the University of Gävle, Gävle, Sweden, and the Ph.D. degree in telecommunications from UPV, in 2004 and 2009, respectively. During the doctoral studies, he was a Guest Researcher at the Royal Institute of Technology, Stockholm, Sweden, the University of Turku, Turku, Finland, and the Technical University of Braunschweig, Braunschweig, Germany. He also performed an internship at Ericsson Eurolab, Germany. From 2010 to 2011, he was a Post-Doctoral Guest Researcher at the Fraunhofer Heinrich Hertz Institute, Berlin, Germany. He is currently a Senior Researcher (Ramon y Cajal Fellow) with the iTEAM-UPV, where he leads a research group working on multimedia broadcasting, in particular on the optimization of 3GPP multimedia broadcast multicast services and digital video broadcasting (DVB) systems. Since 2008, he has been actively participating in the European digital television standardization forum DVB. He also participated in the validation of DVBT2, and in the standardization processes of its mobile profile T2-Lite and its handheld evolution DVB-NGH. He also contributed to the DVB-T2 implementation guidelines, and co-edited the implementation guidelines for upper layer forward error correction. He was very much involved in the promotion and adoption of DVB-T2 in Colombia, and since the second half of 2012, he has been working with the spectrum regulator on the spectrum and network planning and optimization of DVB-T2. Since then, he is also a Visiting Professor with the Sergio Arboleda University of Bogota, Bogota, Colombia. He has edited the book entitled, Next Generation Mobile Broadcasting (CRC Press), and was the Vice-Chairman of the Modulation and Coding Ad-Hoc Group of the ATSC 3.0 standardization process.

Jaime López-Sánchez received Electronic Engineering degree from the Universidad Distrital Francisco José de Caldas, Bogotá, Colombia, and the Ph.D. degree in telecommunications from the Universidad Politécnica de Valencia, Valencia, Spain, in 2005 and 2014, respectively. He worked as an Emissions and Transmission Engineer at the television channel Caracol Television S.A., Bogota, from 2005 to 2008. During the doctoral studies, he was a Guest Researcher at the Institute for Communications Technology, Technische Universität Braunschweig, Braunschweig, Germany, for three months. He has participated in several research and development projects such as FURIA, AV-MOV, and Redes Híbridas in the study and research of digital video broadcasting (DVB) technologies. He was the recipient of the first prize in the research contest "Valencia idea 2010" in the category "Information and Communication Technologies." he was very much involved in the promotion and adoption of DVB-T2 in Colombia, and since the second half of 2012, he has been working with the spectrum regulator on the spectrum and network planning and optimization of DVB-T2. His current research interests include new technical solutions in the evolution of DVB standards for provisioning of advanced multimedia services in digital television networks.

Gerardo Martínez-Pinzón is a researcher at the Universitat Politècnica de València. He received the Telecommunications Enginnering degree in 2007 from the university Unidades Tecnológicas de Santander, Colombia. In 2013 he graduated with honors in Telecommunications Engineering in a double degree agreement between the Universitat Politècnica de València and the Universidad Santo Tomás de Aquino in Colombia. In 2013 he obtained a second M.Sc. in Communications and Development of Mobile Services. Since 2012 he has been participating in cooperation projects between the iTeAM and the Agencia Nacional del Espectro (ANE) from Colombia regarding to electromagnetic compatibility studies which establish the technical conditions for the deployment of DVB-T2 networks in Colombia. His research activities are focused on optimization, DTT network planning and compatibility studies with other technologies as LTE, PMR, etc.

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Manuel Fuentes received the Telecommunications Technical Engineer (Image and Sound) degree from the University of Alicante, Spain, in 2009, and he graduated with honors in Telecommunications Engineering at the Universitat Politècnica de València, Spain in 2012. In 2013 he also obtained the M.Sc. degree in Communications Technologies, Systems and Networks. Currently, he is carrying out his Ph.D. degree in Telecommunications in the Institute of Telecommunications and Multimedia Applications (iTEAM), where he is working since 2012. He participated in several R&D projects founded by the Agencia Nacional del Espectro (ANE) from Colombia, where his research interests were focused on protection ratio measurements and network planning activities between DTT and IMT 4G (LTE) technologies. He is a current member of the DVB European forum and the ATSC forum, contributing to the ATSC 3.0 standardization process. His current research interests include innovate techniques in Bit Interleaved, Coding and Modulation (BICM) and MIMO systems, such as Non-Uniform Constellations (NUC) or Signal Space Diversity (SSD).

Prof. Narcís Cardona was born in Barcelona, Spain. He received the M.S. degree in Communications Engineering from the ETSI Telecommunications at the Polytechnic University of Catalunya in 1990, and the Ph.D. in Telecommunications from the Polytechnic University of Valencia in 1995. Since October 1990, he is with the Communications Department of the Polytechnic University of Valencia (UPVLC). Prof Cardona is in head of the Mobile Communications Group at the UPVLC, with 30 researchers including assistant professors & research fellows. Additionally he is the Director of the Mobile Communications Master Degree (since 2006) and Vice-Director of the Research Institute of Telecommunications and Multimedia Applications (iTEAM) since 2004. Prof Cardona has led and participated to National research projects and to European projects, Networks of Excellence and other research forums, always in Mobile Communications aspects. At European scale, he has been Vice-Chairman of COST273 Action, Chair of the WG3 of COST2100 in the area of Radio Access Networks, and he is currently the Chairman of the EU Action COST IC1004 since May 2011. Prof Cardona is also member of the Steering Board of METIS (7FP), also on Future Mobile Communications Technologies. From his research work, Prof Cardona has authored 8 patents, several books and above 160 research papers. His current areas of interest include mobile channel characterisation; planning and optimisation tools for cellular systems, RRM techniques applied to personal communications and broadcast cellular hybrid networks.