Coverage Optimization and Power Reduction in SFN Using Simulated Annealing

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***Abstract*—An approach that predicts the propagation, models the terrestrial receivers and optimizes the performance of single frequency networks (SFN) for digital video broadcasting in terms of the final coverage achieved over any geographical region, enhancing the most populated areas, is proposed in this paper. The effective coverage improvement and thus, the self-interference reduction in the SFN is accomplished by optimizing the internal static delays, sector antenna gain, and both azimuth and elevation orientation for every transmitter within the network using the heuristic simulated annealing (SA) algorithm. Decimation and elevation filtering techniques have been considered and applied to reduce the computational cost of the SA-based approach, including results that demonstrate the improvements achieved. Further representative results for two SFN in different scenarios considering the effect on the final coverage of optimizing any of the transmitter parameters previously outlined or a combination of some of them are reported and discussed in order to show both, the performance of the method and how increasing gradually the complexity of the model for the transmitters leads to more realistic and accurate results.**

***Index Terms*—DVB systems, propagation prediction, simulated annealing, single frequency network optimization.**

I. Introduction

IN the latest decade, the deployment of digital video broadcasting (DVB) systems, together with the growing demand for services and contents by users, has forced operators to meet quality of service (QoS) criteria while providing high bit rate, information security and error protection [1], [2]. Such DVB systems including DVB-T, DVB-H and DVB-T2 [3]–[7], can be deployed using either multiple frequency networks (MFN) or single frequency networks (SFN), and operators exploit the benefits of the SFN against the MFN topology when combined with the use of orthogonal frequency division multiplexing (OFDM) [8], [9].

The SFN is a better approach in terms of frequency and power efficiency than MFN [10], [11]. On the one hand, the fact that all transmitters use the same frequency band leads to an efficient use of the available bandwidth and eases the radio-planning process. On the other hand, the network gain, i.e. the diversity gain provided by the SFN architecture improves the overall performance of the broadcasting network, increasing coverage over larger geographical areas, reducing the power and saving frequency spectrum against analog networks.

However, in the SFN all transmitters broadcast synchronously the same symbol at the same frequency band, and some adverse effects must be overcome. Specifically, this SFN nature leads to an important artificial multipath propagation, i.e. signals or echoes at the receiver side are combined and depending on their propagation delays it can cause self-interference and intersymbol interference (ISI), more relevant for very far-away transmitters [12], [13]. The use of OFDM in DVB-T systems, exploiting the ability of the OFDM receivers to work in multipath environments helps to mitigate those effects.

The multicarrier OFDM modulation technique [9] provides a robust mechanism against frequency selective fading and narrowband interferences in multipath environments. On the one hand, the aim of dividing the information to send into several orthogonal subcarriers is to mitigate the co-channel interference, trying to minimize the impact on the quality of a small information loss at the receiver side by means of error control techniques. On the other hand, the ISI is reduced by copying the initial or final part of the OFDM symbol during the guard interval or applying other techniques, such as using a suitable synchronization strategy for the fast Fourier transform (FFT) window positioning at the receiver side or delaying the symbol transmission from transmitters [14].

Thus, the network-generated self-interference can be kept low enough by a careful choice of different system parameters [13], [15], [16]. The availability of approaches to be applied during the planning, deployment or improvement stages of SFN is of paramount importance for network operators. The optimization of different network parameters such as transmitters static delays or powers can lead to the reduction of self-interference, improving that way the effective coverage over the area. For instance, introducing appropriate static delays at the transmitters makes it possible to act on the pre- and post-echoes at the receiver side and the same idea relies on transmitters power reduction, leading to self-interference reduction in certain directions. Furthermore, maintenance and deployment costs are also concerned, and the optimization of the number of transmitters, their locations and associated powers can lead to economic efficient SFN.

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In the latest years, heuristic optimization algorithms such as the particle swarm optimization (PSO), simulated annealing (SA) and genetic algorithms (GA) [17]–[19], have been successfully applied in many scientific areas, including the optimization of mobile wireless systems and SFN. Based on recent literature, these algorithms have been successfully applied to optimize the locations, transmission powers and static delays of the transmitters within the network. For instance, in [20] the optimization of transmitter powers and locations along with antenna heights in SFN is formulated as a discrete optimization problem solved by SA. In [21], [22], the SA and GA algorithms are devoted to optimize the location as well as number of transmitters, considering a discrete set of potential candidates and trying to maximize the percentage of covered traffic with the least economical cost, i.e. reducing the number of transmitters as far as possible. Furthermore, GA are applied in [23] to optimize the number of transmitters along with its power and in [24] to improve the SFN planning form the energy efficiency point of view in terms of CO_2 reduction by switching on/off transmitters at specific sites and choosing for them the best power and antenna height amongst a discrete set of values. Moreover, the type of antenna at the transmitter side and its relative orientation in azimuth and elevation can be included as unknowns of the planning problem, as in [25] for cellular networks. The reduction of self-interference in SFN is accomplished in [26], [27] using SA and GA to optimize the internal static delays to be applied at transmitters. The authors have already tackled self-interference reduction for coverage optimization in [28]–[31] using metaheuristics such as the SA, PSO and a hybrid PSO combining real and binary versions of the PSO algorithm, but optimizing not only static delays but also controlling the gain of transmitter sector antennas, switching them on/off if necessary and their relative orientation in azimuth.

In this work, an approach to optimize the coverage in SFN for DVB-T, DVB-H or DVB-T2 systems, using SA as the optimization method, is presented. The approach aims to optimize the coverage over a certain geographical area reducing at the same time the resources as much as possible by switching-off as many transmitter sector antennas as possible, i.e. the reduction of self-interference is performed by optimizing for every transmitter within the SFN the static delay, the gain of sector antennas and their relative orientation in both azimuth and elevation. A thorough analysis for realistic SFN has been carried out including: 1) techniques to overcome the main drawback of the heuristic methods, i.e. reducing the computational cost by filtering appropriately the information of the digital terrain model (DTM) used, 2) a study of the performance of the approach when the number and type of transmission parameters to be optimized is increased gradually and, finally, 3) the effect of the population density has been considered, differentiating between urban and rural areas, i.e. different QoS to meet, favoring urban coverage.

This paper is organized as follows. In Section II, a detailed description of the approach proposed to optimize the coverage of SFN taking into account the orography of the terrain, the specifications for both transmitter and receiver sides, along with certain QoS requirements, is presented. The main features, parameters and settings of the heuristic SA algorithm considered to carry out the optimization task are described in Section III. Results analyzing the effect of decimation and elevation filtering techniques on the computational cost and coverage, along with a comparison between the performance of the SA algorithm when different SFN transmission parameters are considered as the unknowns during the optimization process are summarized and discussed in Sections IV and V, respectively. Finally, the main conclusions of the work are outlined in Section VI.

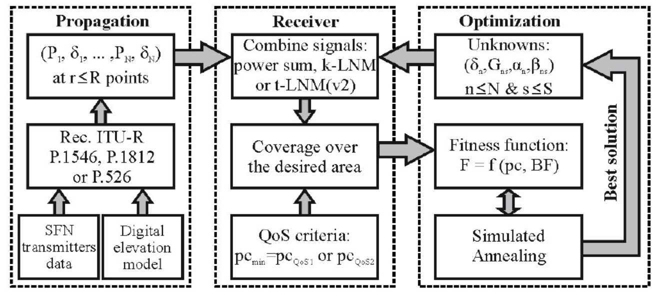

Fig. 1. Block diagram of the SFN optimization model.

II. Description of the Approach

The approach proposed is shown in Fig. 1. The method consists of three interconnected blocks devoted to model the propagation, the terrestrial receiver and the optimization core in such a way that the all three parts work as a whole, as described in the following subsections.

A. Propagation Prediction Method

Let us consider a SFN consisting of N transmitters. First of all, the contribution of the set of transmitters at each receiving location must be estimated according to a suitable propagation prediction method. Two prediction methods for point-to-area terrestrial services in the UHF band provided by ITU-R P.1546, P.1812, as well as the propagation by diffraction models of the ITU-R P.526 have been considered [32]–[34].

According to the principles of each ITU propagation model, its choice and application can lead to significant differences on the final coverage achieved. For instance, the ITU-R P.526 introduces a thorough analysis of the orography, evaluating the diffraction assuming several models depending on the number, type of obstacle and path geometry as well. On the contrary, the ITU-R P.1546 is based essentially on statistical analysis of experimental data, makes a light study of terrain clearance and clutter obstructions and is not suitable for hilly regions in which relevant obstacles are close to either transmitter or receiver sides, or far away from the receiver (more than 16 km). Furthermore, for flat-terrain scenarios this ITU propagation model introduces significant electric-field prediction differences with any other model when the effective height of the transmitter antenna is lower than 10 m, [35], [36]. Finally, the ITU-R P.1812 complements and overcomes some limitations of the P.1546, introducing a path-specific propagation method.

In order to apply such prediction methods to any path profile, the SRTM nearly 90 m resolution digital elevation models (DEM) provided by the NASA [37] have been used and appropriately processed by a geographic information system (GIS) based application. In addition, a 1:25000 national topographic data base with details of the buildings has also been considered to take into account the effect of the populated areas.

Basically, this block returns the signal strength (P_n, $1 \le n \le N$) and propagation delay (δ_n, $1 \le n \le N$) associated with each transmitter ($1 \le n \le N$) at each receiver point ($1 \le r \le R$) inside the geographical area under analysis.

B. Model for the Terrestrial Receivers

The SFN transmission can be considered as a severe form of multipath propagation, so all the signals arriving at each receiving location from each transmitter must be properly treated in the OFDM receivers to maintain the spectrum efficiency. Basically, the receiver block synchronizes and combines all these echoes to obtain the useful and interfering components at every point of the meshed area, i.e. the aggregate C and I, respectively.

In this work, based on the time instant, t, in which each signal arrives at every receiving location, the receiver mask in (1) weighs up the completely or partially contribution of each signal to the C and I components [14],

$$\omega_n = \begin{cases} \left((T_u - t)/T_u\right)^2 & \text{if } \left(T_g - T_p\right) < t \le 0 \\ 1 & \text{if } 0 < t \le T_g \\ \left(\left(T_u + T_g - t\right)/T_u\right)^2 & \text{if } T_g < t \le T_p \\ 0 & \text{otherwise} \end{cases}, \quad (1)$$

in which the useful symbol length, T_u, the guard interval, T_g, and the time limit during which the echoes can positively contribute to the suitable recovery of the information sent, $T_p = 7T_u/24$, depend on the DVB-T mode considered [3].

Moreover, the synchronization strategy chosen for the FFT window positioning at the receiver side also plays a key role as it influences the performance of the OFDM systems in such a way that an efficient technique can lead to a significant reduction of the harmful effect of the pre-echoes and post-echoes arriving at each location. In spite of the fact that this task depends on the manufacturer, several strategies can be found in the literature, such as the center of gravity (CG), strongest signal (SS), first signal above a threshold level (TL) or quasi-optimal (QO) [14].

Next, once the synchronization strategy and the receiver mask in (1) have been applied, the power sum, k-LNM or t-LNM (v2) combination methods can be used to determine the aggregate C and I components at each receiving location [13]. On the one hand, the power sum method is a simple and fast procedure based on the mean value of the total field strength, which generally provides an overestimation of the final level, but it does not take into account the statistic nature of the received signals at any point inside a local area. On the other hand, the k-LNM and t-LNM (v2) techniques normally obtain a more realistic estimation of the combined field strength, considering the combination of a set log-normally distributed values. However, the accuracy of the k-LNM method depends on choosing an appropriate value for the constant k and the t-LNM (v2) technique involves a more complex calculation process to determine the mean and standard deviation of the combined field strength. Regardless of the method, the standard deviation of the individual signals arriving at each point, i.e. the location variation, has been set to $\sigma_n = 5.5$ dB.

Once the signals have been combined, the carrier to interference-plus-noise ratio, *CINR*, can be evaluated at each receiving location ($1 \le r \le R$) as given in (2), considering a SFN consisting of N transmitters, $A = \{1, \ldots, N\}$, and that there are other M transmitters from other networks operating at the same frequency, $B = \{1, \ldots, M\}$, and working as interferers.

$$CINR_r = \frac{\sum_{n \in A} P_n \omega_n (\delta_n - \delta_0)}{\sum_{n \in A} P_n [1 - \omega_n (\delta_n - \delta_0)] + \sum_{n \in B} P_n + N_0} \quad (2)$$

In (2), P_n is the power received from the n-th transmitter, ω_n the value of the weighting mask in (1) and δ_n the n-th propagation delay related to the synchronization time reference, δ_0. In this work, the interference from neighboring SFN has been discarded, so the term $\Sigma_{n \epsilon B} P_n$ in (2) has been removed. Moreover, a DVB-T system with an 8 MHz channel along with 7 dB noise figure for the receivers has also been considered, so the background noise power level has been set to $N_0 = -99.12$ dBm, assuming an absolute temperature of 290 K.

Based on the minimum *CINR* required at every receiver site to consider that a location is properly covered, $CINR_{min}$, the associated coverage probability, *pc*, can be evaluated at that point and thus at every local area, according to (3), [38], [39].

$$pc = Q\left(\frac{CINR_{\min} - (m_C - m_I)}{\sqrt{\sigma_C^2 - 2r_{CI}\sigma_C\sigma_I + \sigma_I^2}}\right) \quad (3)$$

In (3), m_C, σ_C, m_I and σ_I are the means and standard deviations of the aggregate C and I components, respectively, obtained through the combination of the log-normal signals. Moreover, r_{CI} is the correlation coefficient between both C and I components, which can usually be considered as zero although some authors propose calculation methods and analysis of its effect [39], and Q is the normalized inverse cumulative distribution function. It must be noticed that in the m_I term it has also been added N_0.

Finally, this receiver block evaluates the coverage at every receiving location according to the QoS requirements imposed by the user. In this case, every point representing a local area will be considered as covered if the coverage probability, *pc*, exceeds a threshold value, pc_{min}, which can take two different values, $pc_{QoS1} = 90\%$ or $pc_{QoS2} = 70\%$ when $CINR_{min} = 17.3$ [3], depending on whether the designer has imposed "good" or "acceptable" QoS, and just to distinguish between densely populated and rural areas. Based on the specifications used in Spain for the deployment of SFN for terrestrial digital television services [40], the DVB-T 8K1/4 mode system (useful symbol $T_u = 896$ µs and guard inteval $T_g = 224$ µs) with a 64-QAM modulation and a 2/3 code rate has been considered, achieving a useful bit rate of approximately 19.91 Mbps [3].

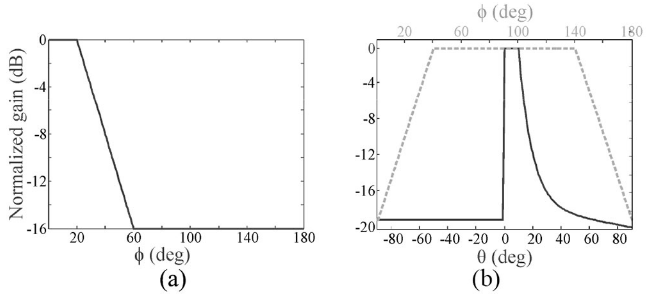

Fig. 2. (a) Terrestrial receiver antennas, detail of the azimuth radiation pattern. (b) Transmitter sector antennas, detail of the azimuth and elevation radiation pattern.

C. Antennas

Regarding the antennas, two different situations have been considered. As the first option, OPT1, let us assume 90 degrees omnidirectional sector antennas in transmission ($S = 4$ sectors) as well as directive antennas in reception with the radiation pattern shown in Fig. 2(a), exhibiting a 55 degrees half-power beamwidth, meeting the specifications in azimuth defined in [41] for the reception of DVB-T services in the IV and V bands. Moreover, a second option, OPT2, considers more realistic radiation diagrams for each sector antenna at the transmitters side, defined as the product of a sectored and a cosecant squared pattern [Fig. 2(b)]. The same mask in azimuth is kept at the receiver side, but now replicated only for 45 degrees in elevation, that resembles fixed TV reception more accurately. Regardless of the case, either OPT1 or OPT2, the receiver antenna is physically pointed during the optimization process to that transmitter from which it receives the strongest signal.

D. Optimization Process

An optimization process has to be carried out in an attempt to improve the coverage within the limits of the desired region. In this block, despite the fact that several heuristic approaches are available and have already been used previously by the authors [28]–[31], the SA algorithm has been chosen and used in this work to find the optimal configuration for several SFN transmission parameters as selected by the user (U unknowns), by modifying iteratively all the dimensions contained in the vector V described in (4), representing the set of parameters to be optimized. The only relationship between the physical problem and the optimization process is given by means of a fitness function, F, which iteratively tests the accuracy of each solution provided by the SA algorithm. The cost function to be minimized is given in (5) and represents the sum of the errors associated with each point inside the meshed area, i.e. those locations without coverage. In order to take into account the effect of the populated areas during the optimization process, a building factor weight, F_r, related to the density of buildings at each local area, has been considered to penalize those populated areas without coverage, as given in (6). In this way, the SA algorithm gives priority to those areas in which the demand for services and contents is higher, because if the r-th receiving location is covered ($pc \geq pc_{min}$) no error is added to the fitness function but, on the contrary, a constant proposed by the authors between 1 and 4 is added to the residual error depending on if there is a low ($BF = 1$), medium ($1 < BF < 5$) or high ($BF \geq 5$) density of buildings, information obtained from a shapefile of the region [42].

$$V = (V_1, \ \ldots, \ V_u, \ \ldots, \ V_U) \tag{4}$$

$$F = \sum_{r=1}^{R} F_r \tag{5}$$

$$F_r = \begin{cases} 0 & if \ \ (pc_{min} \geq pc) \\ 1 & if \ \ (pc_{min} < pc) \ \& \ (BF = 0) \\ 2 & if \ \ (pc_{min} < pc) \ \& \ (BF = 1) \\ 3 & if \ \ (pc_{min} < pc) \ \& \ (1 < BF < 5) \\ 4 & if \ \ (pc_{min} < pc) \ \& \ (BF \geq 5) \end{cases} \tag{6}$$

The SA algorithm can optimize for each transmitter of the SFN the static delay to be applied ($0 \leq \delta_n \leq T_g$ μs), the gains of the 90 degrees sector antennas ($-20 \leq G_{ns} \leq 0$ dB) or equivalently the EIRP or ARP of the sectors and their relative orientations in azimuth ($-45 \leq \alpha_n \leq 45$ deg) and elevation ($0 \leq \beta_{ns} \leq 20$ deg).

E. Reduction of the Computational Cost

Heuristic optimization algorithms are iterative intensive search methods whose main drawback concerns the computational cost, which increases dramatically with the number of unknowns. Regarding the SFN optimization, the number of unknowns strongly depends on the number of transmitters, and thus, on the parameters to optimize for each one; so the easiest choice to reduce the computational cost is to cut down on the number of transmitters. However, if a predefined SFN is considered and the number of transmitters cannot be modified, other alternatives must be investigated. Therefore, taking into account that the highest percentage of the overall CPU time is spent evaluating the fitness function, the only feasible way to reduce the computational cost is by decreasing the number of receiving locations that contribute to the fitness, as long as the final coverage over the desired area is not penalized.

During the iterative process, the SA algorithm must calculate the coverage at each point inside the meshed area, so the computational time spent evaluating the fitness function is directly related to the number of receiving locations. Thus, in this section decimation and elevation filtering techniques are proposed to reduce the number of points that contribute to the fitness evaluation.

1) Decimation: The decimation technique filters the DEM in both spatial directions x and y with a regular step D, regardless of aspects such as the population density. Let us suppose that the area depicted in Fig. 3 is divided into $C_x \times C_y$ square cells 92.5 m side [37]. Therefore, if decimation is not applied, $D = 1$, the number of points that contribute to the fitness function is equivalent to the number of cells within the meshed area, so the SA algorithm requires a computational time, t_{CPU}, to evaluate the residual error at each iteration. However, if only one of every D points is considered by the SA algorithm, the computational time required to evaluate the fitness function, t_{CPU_D}, is reduced by a factor of around D^2 according to (7),

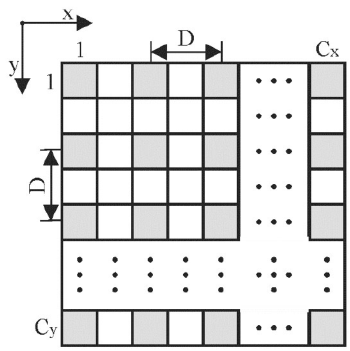

Fig. 3. Decimation of the DEM with a step D, in this case D = 2.

demonstrating the usefulness of decimation from the point of view of CPU time. It must be remarked that more than 99.5% of the CPU time required by the SA at each iteration devotes to fitness computation.

$$t_{CPU\_D} \approx t_{CPU}/D^2 \quad (7)$$

Furthermore, the number of points considered during the optimization process, directly related to the value of D, cannot be reduced just to save CPU time. According to the ITU-R P.1546 and P.1812, the field strength estimations are valid in local areas of 500 × 500 m^2, providing a representative value of standard deviation for the location variability as a function of the frequency and the environment. This fact states that according to the cell size (92.5 m), the decimation step should never exceed D = 4 (equivalent local areas of 462.5 × 462.5 m^2).

2) Elevation Filtering: In geographical areas with a complex orography, the highest elevation sites are practically deserted; in most cases corresponding with rural areas whose analysis and optimization can be avoided without influencing on the final coverage estimations.

Let us analyze the joint effect of both decimation and elevation filtering. Considering a generic elevation, h, and a decimation step, D, the computational cost at each iteration, $t_{CPU\_D\&h}$, can be defined as a relationship between the number of receiver points considered when both decimation and elevation filtering are applied, $NP_{D\&h}$, and the total number of cells in which the region is divided, C_xxC_y, according to (8). If D = 1, the CPU time saving is only associated with elevation filtering.

$$t_{CPU\_D\&h} \approx t_{CPU}\left(NP_{D\&h}/\left(C_xC_y\right)\right) \quad (8)$$

III. Simulated Annealing

The SA is a stochastic optimization method based on the fundamentals of thermodynamic systems that evolves from a single solution without retaining past or recent information about the process [18]. Initially proposed as an effective alternative to solve large and complex combinatorial problems, it has been successfully applied in a great variety of scientific and technical areas, due to its ability to find quasi-optimal solutions in non-linear, high dimensional and multimodal search spaces. Basically, the SA algorithm imitates the annealing of a metal, emulating the energy changes caused in the system as the temperature decreases slowly from a high initial temperature, T_{a0}, for which the particles are randomly distributed and have a notable mobility, until the structure reaches the thermal equilibrium.

At each iteration of the algorithm, $i \rightarrow i + 1$, considering a specific temperature, T_a, one dimension of the solution vector V in (4) is disturbed and the energy change experienced by the system, ΔF, measured in terms of the fitness function in (5), is calculated. Next, if the energy decreases, $\Delta F < 0$, the new solution, V_{i+1}, is closer to the minimum energy state of the structure than the current solution, V_i, so the proposed vector is accepted. Otherwise, $\Delta F \geq 0$, based on the Metropolis criterion, the Boltzmann's Probability Distribution given in (9), *BPD*, is used to decide whether the new vector V_{i+1} must be selected or not. In this way, especially when the temperature T_a is high, the SA algorithm can accept lower quality solutions, providing a protection mechanism from getting trapped in local optimums during the initial iterations of the algorithm. However, as the temperature T_a decreases, the probability to select a worse solution decreases; focusing the search in the surroundings of V_i.

$$BPD\,(V_i \rightarrow V_{i+1}) = \begin{cases} \exp\left(-\Delta F/T_a\right) & \text{if } \Delta F \geq 0 \\ 1 & \text{if } \Delta F < 0 \end{cases} \quad (9)$$

Considering V_i or V_{i+1} as the new starting point, depending on the result obtained in (9), the previous process is repeated for *NS* cycles, trying to reach the minimum energy state of the system at each temperature T_a. Moreover, to adjust the variability that can take each parameter, the search for the thermal equilibrium is repeated during *NT* cycles before reducing the temperature according to a reduction temperature coefficient, *RTC*. Finally, the process is repeated iteratively during the maximum number of fitness evaluations allowed or until a residual error imposed is reached [43].

In this work, based on previous studies [29], [30], the following parameters for the SA algorithm have been considered: initial temperature, T_{a0} = 0.5, temperature reduction coefficient, *TRC* = 0.1, and number of cycles to reach the thermal equilibrium and to adjust the variability, *NS* = 20 and *NT* = 5, respectively.

IV. Results I: Computational Cost Reduction

In this section, the effect of both decimation and elevation filtering techniques on the performance of the approach has been analyzed. Let us consider as a canonical problem to validate the efficiency and usefulness of the two strategies a SFN consisting of N = 11 transmitters operating at 786 MHz (channel 60 in Spain) with the distribution, sector antenna orientation (starting with G_{ns} = 0 dB and α_n = 0 deg) and initial transmission powers as represented in Fig. 4. The SFN must provide DVB-T services in Gipuzkoa, a province in northern Spain characterized by a complex orography with an extension of 1980 km^2. The area under analysis is modeled using R = 626106 receiving locations (598 rows × 1047 columns using the square grid 92.5 m side [37]), of which only $C_x \times C_y$ = 315844 are within the geographical limits of

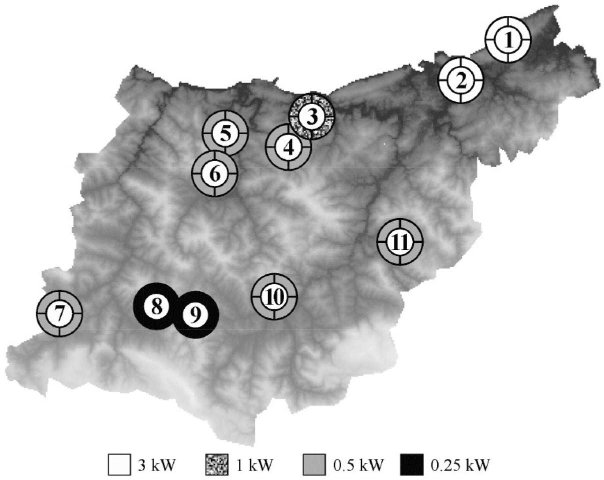

Fig. 4. SFN in Gipuzkoa. Initial transmission powers.

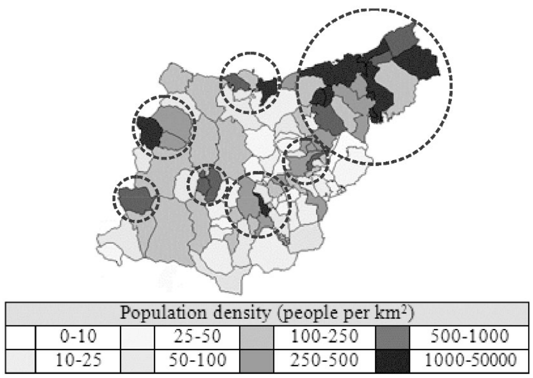

Fig. 5. Population density in Gipuzkoa. The areas with more stringent QoS requirements are depicted with a dashed line.

the province and are the pool on which the SA will focus the coverage optimization. Moreover, a DVB-T 8K1/4 mode system is considered, the power sum method is used to combine the signals at the receiver side and the strongest signal synchronization strategy is chosen for the receiver FFT window positioning [14].

Based on the population density shown in Fig. 5 [44], a more stringent QoS criteria, pc_{QoS1} = 90%, has been imposed on those city centers with more than 250 people per km^2, highlighted with dashed circles in the figure, whereas a lower threshold, pc_{QoS2} = 70%, has been considered to evaluate the coverage outside the main population areas, assuming for both urban and rural regions a $CINR_{min}$ = 17.3 dB [3].

Assuming the OPT1 case, the SA algorithm must optimize for each transmitter in the network ($0 \leq n \leq 11$) the static delay to be applied ($0 \leq \delta_n \leq 224$ μs), the gains of the four 90 degrees sector antennas ($-20 \leq G_{ns} \leq 0$ dB, $1 \leq s \leq 4$ sectors) and their relative orientations in azimuth ($-45 \leq \alpha_n \leq 45$ deg), trying to maximize the percentage of sites covered inside the geographical area. Therefore, V in (4) is a 66-dimensions vector. The settings for the SA algorithm outlined in Section III have been considered, assuming that the maximum number of fitness evaluations allowed is 25000.

TABLE I
NUMBER OF LOCATIONS FOR SEVERAL DECIMATION STEPS
(INTEL CORE I7 @ 2.93 GHZ PROCESSOR)

D	Locations			Locations with buildings (%)
	Number	%	CPU (s/iter)	
1	315844	100	1.75	100
2	78955	25	0.44	24.51
3	35103	11.11	0.19	11.09
4	19737	6.25	0.11	6.11

TABLE II
COVERAGE RESULTS OBTAINED FOR SEVERAL DECIMATION STEPS

D	Coverage (%)			
	Initial	SA	ΔC	Locations with buildings
1	61.52	69.74	13.36	67.70
2		70.07	13.90	67.95
3		70.40	14.44	68.36
4		69.88	13.58	67.58

A. Effect of Decimation

In order to analyze the effect of decimation on the CPU time as well as the coverage, the SA optimization has been carried out considering a step between locations $D \in [1, 4]$. Furthermore, the method ITU-R P.1546 has been used to model the propagation.

Table I summarizes the savings achieved in terms of the CPU time in seconds per iteration (s/iter) as the step factor D increases, and in which the percentages take as reference the original DEM with no decimation, i.e. D = 1 and local areas of 92.5 × 92.5 m^2. In this way, it is shown that the number of points that contribute to the fitness value can be reduced significantly. The right column in Table I is merely informative and gives an idea of how the D factor also reduces the percentage of populated areas that are kept during the analysis after decimation takes place. Furthermore, it is also necessary to analyze the influence of the D factor on the coverage.

The results obtained in terms of the coverage achieved over the whole region before and after the optimization is carried out are summarized in Table II when averaging the results of 25 independent runs of the SA-based approach, just to take into account the stochastic nature of the optimizer. The final improvement, ΔC, is calculated as given in (10). The right column in Table II gives information about the percentage of populated sites inside the geographical area that are covered once the SA algorithm has finished.

$$\Delta C\,(\%) = 100\left(\frac{Coverage_{SA} - Coverage_{Initial}}{Coverage_{Initial}}\right) \qquad (10)$$

It is inferred from the results summarized in Tables I and II that a D_{OPT} = 3 can be considered as an optimal value for the decimation factor, reducing the CPU time by 89.14% when compared to the initial situation (D = 1) and demonstrating that the decimation do not deteriorate the final coverage at all, just the opposite 70.40% against 69.74%. Moreover, if D < 3 the final coverage gets slightly worse as the number of locations increases and slows down the search of the SA, introducing more contributions in (5) that can become noise or

TABLE III
NUMBER OF LOCATIONS WHOSE ELEVATION DO NOT EXCEED 800 M (INTEL CORE I7 @ 2.93 GHZ PROCESSOR)

D	Locations			Locations with buildings (%)
	Number	%	CPU (s/iter)	
1	293962	93.07	1.62	99.12
3	32452	92.44	0.18	99.16

TABLE IV
COVERAGE RESULTS OBTAINED WITH THE LIMITING ELEVATION, H = 800 M

D	Coverage (%)			
	Initial	SA	ΔC	Locations with buildings
1	61.27	70.27	14.69	67.98
3		70.65	15.31	68.50

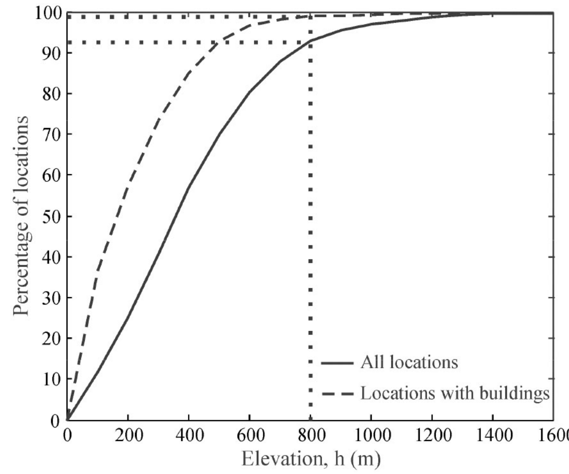

Fig. 6. Distribution of the number of locations with the elevation within the limits of the geographical area in Gipuzkoa.

(a) (b)

Fig. 7. Coverage maps in Gipuzkoa, considering D_{OPT} = 3 and h = 800 m. The covered, not covered, and filtered receiving locations are depicted in light gray, dark gray and black, respectively. (a) Initial. (b) Optimized.

simply disturb the convergence of the algorithm. Conversely, despite the fact that reducing the number of points the SA algorithm can focus the search and speed up the convergence, if the step is too high, $D \geq 4$, too many receiving locations are ignored and the concept of local area and location variability can be lost.

B. Effect of Elevation Filtering

The distribution of the receiving locations against the elevation of the terrain for the region of Gipuzkoa is shown in Fig. 6, from which it can be inferred that more than 99% of the locations with buildings (exactly 99.12% as summarized in Table III) is concentrated in areas whose elevation do not exceed h = 800 m, so this value can be considered as an appropriate elevation threshold. In this way, according to Table III and for D = 1 (D = 3), the number of receiving locations in which the coverage must be evaluated reduces from 315844 (35103) to 293962 (32452), a 6.93% (7.55%) and, consequently a similar reduction will experience the CPU time just by applying elevation filtering.

Taking into account only those receiving locations whose elevation do not exceed h = 800 m to calculate the coverage, the results obtained when averaging 25 independent runs of the SA algorithm are summarized in Table IV, leading to coverage results quite similar to the previous ones presented in Table II. In short, a combination of both decimation and elevation filtering can lead to significant cost reductions, e.g., applying a D_{OPT} = 3 decimation along with an elevation filtering with a threshold level of 800 m, the cost per iteration reduces from 1.75 to 0.18 s, a 89.71%. The joint effect on the coverage of both decimation and elevation filtering for D_{OPT} = 3 and h = 800 m is shown in Fig. 7 for a single run of the SA algorithm.

V. RESULTS II: CAPABILITIES OF THE APPROACH

In this section, representative results along with a discussion showing the impact that different SFN transmission parameters have got on the final coverage achieved are included. The aim is to increase gradually the complexity of the optimization task, increasing the number of transmitter parameters controlled by the optimizer with a dual purpose, on the one hand to test the abilities of the software approach to handle with realistic problems and, on the other hand, to analyze the results as the SFN transmitters, and thus the SFN itself, becomes more and more realistic.

For that dual-purpose goal, the SA algorithm must optimize for each transmitter at least one of the following parameters (or a combination of several ones) trying to maximize the performance of the overall SFN: static delay ($0 \leq \delta_n \leq 224$ μs), sector antenna gains ($-20 \leq G_{ns} \leq 0$ dB) and its relative orientation in azimuth ($-45 \leq \alpha_n \leq 45$ deg) and elevation ($0 \leq \beta_n \leq 20$ deg).

Let us consider a SFN in Ourense, a northern Spanish hilly province with and extent of 7273 km^2. The SFN consists of N = 25 transmitters operating at 802 MHz (channel 62 in Spain), whose locations and initial powers, P_{Tx}, are summarized in Fig. 8 and Table V, respectively. However, it must be emphasized that in some cases the site as well as power for the transmitters of the SFN does not correspond with current real active transmitters, as information is not available from the public institutions. Moreover, the simulation area consists of R = 1799634 receiving locations, from which only $C_x \times C_y$ = 1140805 are within the geographical limits of the region under analysis.

According to the population density in Ourense [44], the five densely populated areas highlighted in Fig. 9 can be

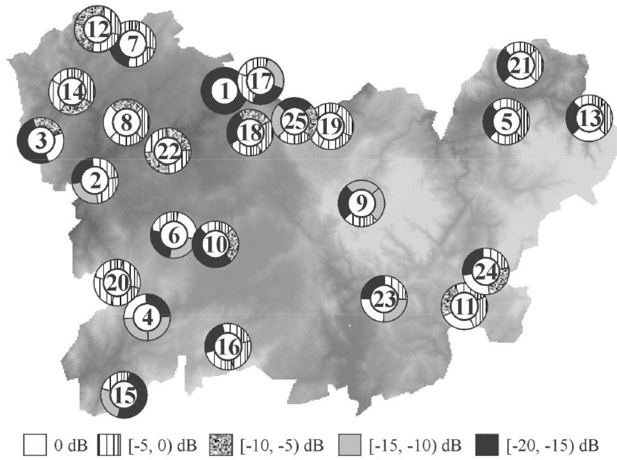

Fig. 8. SFN in Ourense. Detail of sector antennas gain and their relative orientations in azimuth provided by one single run of the SA algorithm considering the ITU-R P.1812 and the k-LNM method.

TABLE V
SA RESULTS OBTAINED FOR THE SFN IN OURENSE

n	P_{Tx} (kW)	δ (μs)	β (deg) 1	2	3	4	α (deg)
1	0.820	144.6	19.93	10.46	18.03	10.42	-24.47
2	0.410	20.2	8.69	4.47	19.58	9.53	7.45
3	0.328	1.2	8.44	13.07	7.18	10.95	20.13
4	0.164	10.5	0.34	0.44	2.46	10.25	2.98
5	0.328	15.1	9.70	19.79	0.09	15.27	43.31
6	0.410	106.1	11.88	0.24	9.77	5.94	-11.29
7	0.820	15.7	10.80	-0.69	9.64	-0.50	-12.50
8	0.820	139.6	12.00	0.30	17.65	0.38	43.46
9	0.328	156.6	16.06	15.33	0.17	10.69	41.52
10	0.410	132.6	9.58	10.34	19.20	1.41	43.36
11	0.164	141.5	13.70	19.87	0.32	7.31	24.91
12	0.820	114.9	10.24	7.54	18.46	8.73	-15.12
13	0.328	32.6	3.62	7.77	0.23	19.19	43.98
14	0.820	178.2	5.46	12.67	0.09	2.30	-29.78
15	0.328	164.6	18.44	0.22	9.73	2.65	-16.18
16	0.410	212.4	9.57	18.87	18.60	17.84	14.91
17	0.164	160.1	7.12	13.20	16.13	7.43	-19.23
18	3.280	160.9	10.09	11.54	0.26	7.64	30.33
19	0.164	204.8	14.52	13.75	12.75	1.06	-25.77
20	0.328	207.8	0.49	0.21	0.19	15.81	-14.39
21	1.640	0.0	7.51	1.02	0.37	3.03	44.81
22	1.640	203.2	14.47	0.48	2.25	19.56	3.08
23	1.640	161.8	16.48	12.73	0.17	2.65	-1.19
24	0.164	179.6	8.14	7.78	0.14	12.60	9.23
25	0.164	204.4	0.12	17.75	19.85	9.38	43.92

defined and two QoS criteria stated. Thus, $pc \geq pc_{QoS1}$ = 90% and $pc \geq pc_{QoS2}$ = 70% are the two QoS thresholds considered for urban and rural regions, respectively, assuming $CINR_{min}$ = 17.3 dB [3]. Moreover, in order to reduce the CPU time and taking into account the results of the previous section, a decimation step D_{OPT} = 3 along with an elevation filtering with a threshold of h = 1200 m have been considered. According to Table VI, for a height of 1200 m, the 99.46% of the inhabited locations are taken into account by the SA algorithm, and the computational cost becomes reduced by a 90%.

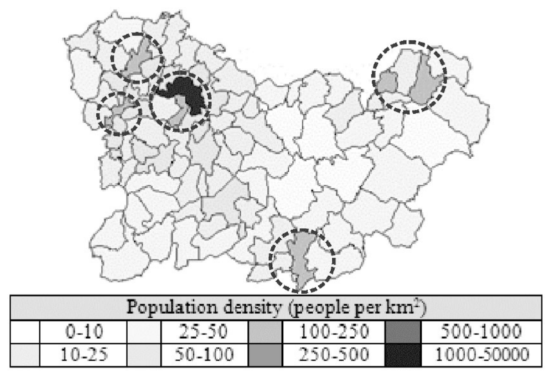

Fig. 9. Population density in Ourense. The areas with more stringent QoS requirements are depicted with a dashed line.

TABLE VI
NUMBER OF LOCATIONS CONSIDERED IN OURENSE (K-LNM COMBINATION METHOD AND INTEL CORE I7 @ 2.93 GHZ PROCESSOR)

D	h (m)	All locations: Number	%	CPU (s/iter)	Locations with buildings (%)
1	2200	1140805	100.00	11.59	100.00
	1200	1030857	90.36	10.47	99.46
3	2200	126753	100.00	1.29	100.00
	1200	114561	90.38	1.16	99.50

TABLE VII
COVERAGE RESULTS OBTAINED IN OURENSE

Unknowns	U	Coverage (%): Initial	SA	ΔC	Locations with buildings	ΔP
δ	25	52.23	72.03	37.91	72.61	0.00
G	100		65.90	26.18	69.20	48.53
δ+G	125		77.53	48.46	79.42	38.63
G+α	125		70.66	35.30	71.72	51.18
δ+G+α	150		79.94	53.06	81.96	41.55
G+β	200		68.08	30.36	70.28	47.12
δ+G+β	225		76.44	46.36	79.00	46.13
G+α+β	225		73.16	40.08	73.70	49.04
δ+G+α+β	250		80.56	54.25	82.54	46.33

As already mentioned in Section II, a DVB-T 8K1/4 mode system has been considered, and the ITU-R P.1812 has been used as the propagation prediction method. Furthermore, the first signal 17 dB below the strongest signal synchronization strategy is used for the receiver FFT window positioning and the k-LNM (k = 0.8) method has been considered to combine the signals at the receiver side [13], [45].

Regarding the SA-based optimization process and the transmission parameters to be optimized, the nine cases summarized in Table VII have been considered, so the dimensions of vector V in (4) can vary from U = 25 to U = 250 unknowns for the 25-transmitters SFN. As already stated in previous paragraphs, the aim is to check the ability of the SA-based approach to manage with a network whose complexity rises up as it becomes more realistic by introducing new transmitter parameters into the optimization process, analyzing at the same time its effect on the coverage achieved. This is represented by the nine-step complexity increasing process summarized in

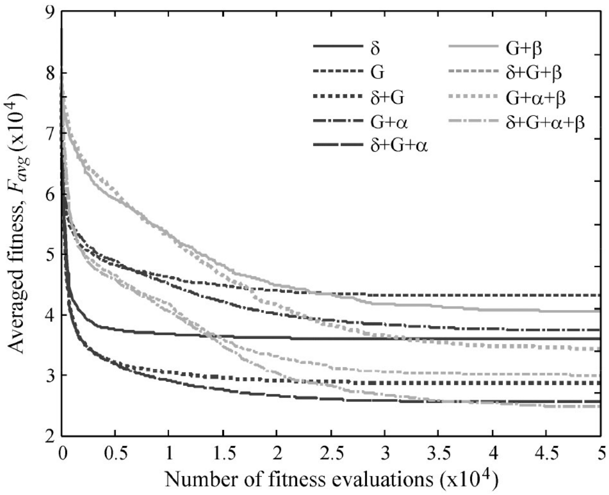

Fig. 10. Evolution of the averaged fitness, *Favg*.

Table VII, first column. Furthermore, the same parameters as the ones considered in the previous section have been assumed for the SA algorithm (T_{a0} = 0.5, *TRC* = 0.1, *NS* = 20 and *NT* = 5), but now considering the more realistic OPT2 case for the antennas and a maximum number of fitness evaluations for the SA termination criteria of 50000.

The results achieved for any of the nine test cases when 25 independent runs have been carried out and properly averaged, are summarized in Table VII. According to these results, static delays (δ) are the parameters that most contributes on their own to reduce the self-interference within the network and, thus, its optimization outperforms significantly the performance of the original SFN, increasing the percentage of locations covered by nearly a 38% (from 52.23% to 72.03%). If the SA-based approach is allowed a greater degree of freedom, and besides the static delay for each transmitter, it can also modify simultaneously other transmitter parameters such as the gain of the sector antennas or its orientation, then the coverage improvement achieved is even more significant and the total percentage of locations covered (or only those with buildings) rises up to 77.53% (79.42%), 79.94% (81.96%), 76.44% (79.00%) and 80.56% (82.54%) when the cases indicated as δ+G, δ+G+α, δ+G+β and δ+G+α+β are considered, respectively. Moreover, the results also show the positive effect on the final coverage of the transmitters sector antennas tilt-angle optimization (β cases). For instance, the results for G (65.90%) and G+β (68.08%) situations demonstrate that modifying the orientation in elevation of the directive sector antennas reduces the self-interference in the network and improves its performance. This last conclusion can be also inferred from the results obtained for the G+α (70.66%) and G+α+β (73.16%) cases. In both cases, more than a 2% coverage improvement has been achieved, representing 176.40 km^2 in terms of the surface inside the region that are now covered. However, including as an extra unknown that tilt-angle (β) influences significantly the optimization process, slowing down the initial convergence of the SA though, in the end, it promotes a harder exploration of the search space driving the algorithm to more promising solutions, as shown in Fig. 10.

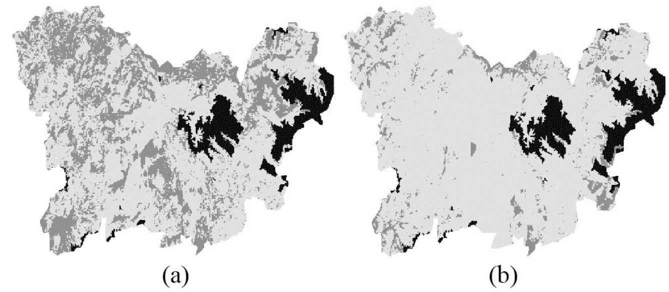

Fig. 11. Coverage maps in Ourense. The covered, not covered, and filtered locations are depicted in light gray, dark gray and black, respectively. (a) Initial. (b) Optimized, but switching off all transmitters sector antennas in the range [−20, −15) dB.

Concerning the power at the transmitters side, the overall power reduction ΔP achieved for any of the nine test cases is quite significant, switching off in some cases (−20 dB gain) many sector antennas of several transmitters, as previously illustrated in Fig. 8. This reduction becomes slightly higher when the SA algorithm focuses only on mitigating the self-interference by reducing the signal strength in certain spatial directions (G, G+α or G+β cases), but this fact leads to a significant reduction of the coverage over the region.

According to the results obtained, a tradeoff between both coverage and power metrics must be established when deciding about the parameters most suitable to be optimized. The most advisable option is to optimize jointly for every transmitter within the SFN its static delay along with sector antenna gains as well as their azimuth and elevation orientations (δ+G+α+β). As a representative example of this particular case, the results achieved for a single run of the SA-based approach are shown in Table V and Fig. 8. The static delays in Table V are referenced to that transmitter with the lowest optimized delay, i.e. transmitter number 21. Furthermore, the SA-based approach suggests lower sector antenna gains for most of the transmitters within the SFN, mitigating that way the interference in certain directions, involving at the same time a high power reduction with regard to the original SFN configuration (51.08%). For instance, if transmitter number 1 is removed from the SFN (all its sector antennas have an optimized gain in the range [−20, −15) dB in Fig. 8), the coverage increases from 83.93% to 83.99% and from 86.31% to 86.37% when all the locations or only those with buildings inside the region are taken into account, respectively. Furthermore, if all the sector antennas depicted in black in Fig. 8 are switched off, the final coverage reaches 84.11% and 86.48%. The initial and optimized coverage maps in this last situation are shown in Fig. 11.

VI. Conclusion

In this paper, the performance and usefulness of an approach to analyze and optimize the performance of SFN for DVB-T services in terms of the final coverage achieved over a desired geographical area, has been presented. The software approach uses a three-block structure mixing up a GIS based application with several propagation prediction methods to model the propagation, specific models for the receivers including some combination methods to emulate the SFN behavior, along with an optimization engine to improve coverage and resources of the SFN.

Different QoS requirements have been considered to account for the effect of the population density, so those receiving locations with more number of buildings have been grouped into regions with more stringent QoS criteria. Appropriate cost weights have been introduced to give priority to those populated areas.

The main drawback of the approach proposed in this work deals with the computational cost. The SA algorithm is an iterative intensive search global optimization method, in which the overall CPU time is proportional to the number of fitness function evaluations, so cutting down on that amount becomes crucial to make the approach computationally efficient. The DEM decimation and elevation filtering have been proposed and applied together achieving CPU time reductions of 90% or even greater as demonstrate the results reported for the scenarios investigated. The reason is that cutting down on the number of receiving locations that contribute to the fitness function during the optimization process, reduces the overall computation at each iteration.

Furthermore, the performance of the optimized SFN has been analyzed when different transmission parameters have been considered as the unknowns during the optimization process, including static delays, sector antenna gains and orientations in azimuth and elevation. The results show that optimizing the static delays is the most efficient way to reduce the self-interference inside the network, although including the sector antenna gains involves a high power reduction. Regarding the orientations of the sector antennas, the optimization of both azimuth and elevation angles helps to improve the performance of the SFN.

Finally, the results included for the SFN analyzed demonstrate the usefulness of the SA-based approach, improving the overall coverage as well as optimizing the resources of the network. In short, the optimal configuration obtained by the SA algorithm for every transmitter within the SFN including parameters such as the static delay and gain along with relative orientations in azimuth and elevation of the sector antennas, not only makes the final coverage over the desired area improve, but it also reduces the deployment and maintenance costs of the SFN just by applying a power reduction in several transmitters, minimizing this way the interference in certain directions of the region.

In spite of the fact that this work has focused on DVB-T networks, the optimization-based approach presented in this work can be also applied to other OFDM based systems like ISDB-T, T-DMB and other future broadcast systems such as the LTE broadcasting mode or the ATSC 3.0 standard.

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