Green Network Planning of Single Frequency Networks

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***Abstract*—This paper investigates the network deployment of single frequency networks (SFN) based on OFDM schemes that are standardized for terrestrial broadcasting systems, for digital audio broadcasting (DAB) and for digital video broadcasting (DVB) systems. The concept of green network planning is presented. The term 'green' refers to low carbon, energy efficiency and low exposure to radiation, parameters important for the sustainable growth. For the purpose of our investigation a mountainous area of Northern Greece is examined, that is described by a digital terrain elevation model (DTEM) and field computations are based on multi shape slope uniform theory of diffraction (UTD) technique. A genetic algorithm (GA) optimization method is developed for the network planning purposes. A comparison between various planning strategies is presented. It is shown that great CO_2 reductions, cost savings and low exposure to radiation can be achieved when the network planning considers a 'green' strategy.**

***Index Terms*—Energy efficiency, exposure to RF radiation, genetic algorithms, green communications, green network planning, single frequency network optimization.**

I. INTRODUCTION

THE optimization and planning of wireless communication networks is a complex procedure and sophisticated techniques have been widely used [1]–[3]. The introduction of additional services, supported by high data rates requires a dense deployment of wireless networks that create concerns on radiation exposure, energy demands and carbon footprint [4] of the sector of telecommunications. Great concerns also arise from the fact that the carbon footprint of the telecommunication industry has been exponentially increased over the recent years. It is shown that the Information and Communication Technology (ICT) sector is responsible for approximately 5% of global electricity demands and carbon emissions are identical to that of airline industry [5], [6]. In wireless communication networks, the operation of transmitting or base stations is responsible for the 70% of the total energy demands of the network. In addition, the operation of transmitting stations to off-grid areas is based on the use of limited energy supply sources like the renewable energy sources, diesel generators and battery banks and this makes energy efficiency of vital importance. It is a global target to reduce the carbon emissions and energy demands by 20% until 2020 [7]. Furthermore, the deployment of numerous communication networks in a given area increases the exposure of humans to RF radiation for which specific guidelines have been issued [8], [9]. This analysis shows that energy efficiency, carbon emissions and health issues are important factors when telecommunication networks are deployed. Finally, energy efficient telecommunication networks present a reduced Operational Expenditure (OPEX) which can be comparable to the Capital Expenditure (CAPEX). In this paper, the green network planning of single frequency networks is presented and various planning strategies are compared in terms of their energy demands, carbon emissions and exposure to radiation.

Single frequency networks are based on OFDM schemes and this provides immunity to severe multipath environments. To limit the effect of interfering signals, longer transmitting symbols are used and complex receiving strategies have been deployed [10]. DVB networks can be deployed for terrestrial broadcasting services (most recent service of DVB-T2) [11], [12] or cooperate with UMTS networks to provide DVB-H to handheld terminals [13]. Network optimization strategies for such systems involve the adjustment of the network parameters that are usually focused on the transmitter position, transmitter height, antenna characteristics and power levels to provide improvements of coverage and QoS. There are numerous techniques found in the literature describing this problem and are usually based on stochastic or evolutionary optimization processes. The most widely used are the simulated annealing, particle swarm methods, integer programming and the genetic algorithms. In [1] a cost optimized network planning strategy for DAB systems is presented based on simulated annealing. The authors introduce weighting factors to the transmitter positions, transmitter heights and power levels to provide a minimal cost network deployment. Comparisons between three different optimization scenarios are also presented. In [14] the authors utilize a particle swarm optimization method to provide a maximum coverage network for DVB services by adjusting the antenna characteristics and symbol durations and delays to the transmitters. A deterministic integer programming optimization strategy for CDMA networks with controlled cell overlap is presented in [2]. This methodology can also be implemented to DVB systems where cell overlap can affect the network gain and interference.

Evolutionary optimization techniques have been widely used to highly complex optimization problems. They present a great diversity of applications. In [3], [15] genetic algorithms and greedy optimization techniques are presented for coverage improvements in cellular systems. In addition, a genetic algorithm technique capable to minimize radiation pollution by cellular systems is presented in [16]. Furthermore, the concept of green cellular is introduced in [17], where the target of the optimization is to reduce the emitted power by mobile stations, by deploying femtocell systems. Techniques for measuring and reducing the exposure to electromagnetic radiation can also be found in [18]–[21].

The optimization strategies described above have as main objective the coverage and QoS improvements or the reduction

Manuscript received December 22, 2009; revised June 18, 2010; accepted June 23, 2010. Date of publication July 19, 2010; date of current version November 19, 2010.

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Digital Object Identifier 10.1109/TBC.2010.2056252

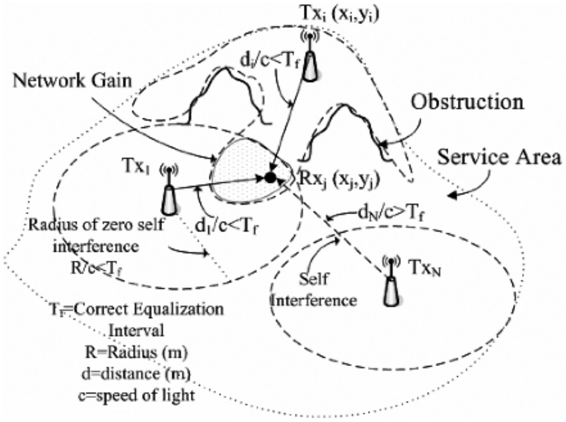

Fig. 1. System model.

of exposure levels. Furthermore, they made use of propagation models that describe field variations based on empirical or semi-empirical techniques, degrading the performance of the optimization. Finally, the planning strategies are based on hypothetical receiving or transmitting positions that do not represent real world scenarios. In this paper, a genetic algorithm optimization technique is developed that has as main objective to deploy a DVB network in a sustainable green base and simultaneously provide an acceptable QoS and coverage. Energy efficiency, low carbon emissions and low exposure to radiation are simultaneously targeted. The field predictions are based on deterministic multiple diffraction formulations, the multi-shape slope UTD technique that has presented a very good agreement with real measurements [22]. A DTEM is used to represent the area under investigation and the network planning targets to deliver DVB services to real cities, towns and touristic areas that exist on this area. Realistic transmitter locations and parameters are also considered to describe in the most effective way the planning of the network. Finally, comparisons of various optimization strategies are discussed.

II. SYSTEM MODEL

The system model is presented in Fig. 1: A set of possible transmitters, Tx_i with $\boldsymbol{N} = \{1, \ldots i, \ldots N\}$ and N representing the maximum number of transmitters is considered. Each Tx has coordinates $\{\mathrm{x_i}, \mathrm{y_i}\}$. The receivers represent real cities, towns and touristic areas of the scenario and are indexed Rx_j, $\boldsymbol{M} = 1 \ldots j, \ldots . M$ where M is the maximum number of receivers. Each Rx has coordinates $\{\mathrm{x_j}, \mathrm{y_j}\}$ and is placed within the service area. External neighboring networks that can introduce potential interference are not considered. The DVB system is deployed in a SFN approach and all the transmitters are assumed to be synchronized. OFDM scheme provides immunity to self interference according to the relative distances and field strength of the arriving signals. The following subsections describe the modeling parameters.

A. Interference Modeling

The QoS at a given location (x, y) within the service area depends on the carrier to interference ratio C/I. The interference is assumed as the self interference caused by the delayed signals and the background noise. According to the used modulation scheme, code rate and channel type, acceptable quality is achieved when the C/I is greater than a specific threshold, U_0. To limit the effect of the delayed signals, longer transmitting symbols are used and receivers with intervals of correct equalization are also utilized [10]. A signal of time interval T_s consists of the useful part, T_u and the guard interval T_{GI}. At the receiver an interval of correct equalization $T_f = 2T_{GI}$ is assumed. Around each transmitter of the scenario a radius of zero and non zero interference is distinguished depending on the guard interval and the interval of correct equalization of the receiver. A simplified weighting function is used to model interfering signals, $w(\delta_i - \delta_0)$ where δ_i represents the relative delay and δ_0 represents the staring point of the receiver detection window (eq. (1)). In equations (1) and (2), P_W is the wanted signals, P_U refers to the unwanted (interfering) signals, P_i is the received field from the ith transmitter and N_0 is the background noise level. In case of other potential interference from neighboring networks, equation (2) is modified with an additional factor in the denominator.

$$w(t) = \begin{cases} 0, & t < 0 \\ 1, & 0 \leq t \leq T_{GI} \\ \left(\frac{T_u - t + T_{GI}}{T_u}\right)^2, & T_{GI} < t < T_f \\ 0, & t > T_f \end{cases} \tag{1}$$

The carrier to interference ratio is computed as

$$U = \frac{P_W}{P_U + N_0} = \frac{\sum\limits_{i \varepsilon N} P_i w(\delta_{\mathrm{i}} - \delta_0)}{\sum\limits_{i \varepsilon N} P_i \left[1 - w(\delta_{\mathrm{i}} - \delta_0)\right] + N_0} \geq U_0 \tag{2}$$

B. Coverage Probability

Coverage probability is computed assuming a location variation of the single field strength that is modeled by a log-normal distribution with standard deviation of 5.5 dB. The coverage probability for a small area around the receiving location, $\mathrm{p_c(x_i, y_i)}$ is:

$$p_c(x_i, y_i) = \Pr\left\{U(x_i, y_i) \geq U_0\right\} \tag{3}$$

The Wilkinson method [23] is used to determine the sum of log-normal stochastic variables. The effect of the interference and noise is assumed independent [1] and the coverage probability is computed according to

$$p_c = \Pr\left\{\frac{P_W}{P_U} \geq U_0\right\} \times \Pr\left\{\frac{P_W}{N_0} \geq U_0\right\}, \forall (x, y) \in M \tag{4}$$

A receiving point is covered with an acceptable QoS only if the total useful signal, C, and the C/I are above the threshold values considered by the service. For digital broadcasting systems the coverage probability should be high enough to overcome the rapid degradation of signal quality caused by the brick-wall effect. For DVB systems p_c should follow the relation $p_c(x_i, y_i) \geq C_0, 70\% \leq C_0 \leq 95\%$.

III. GREEN DEPLOYMENT

The term ‘green’ refers to an energy efficient, low carbon and low exposure network deployment. This section describes the computation of these factors.

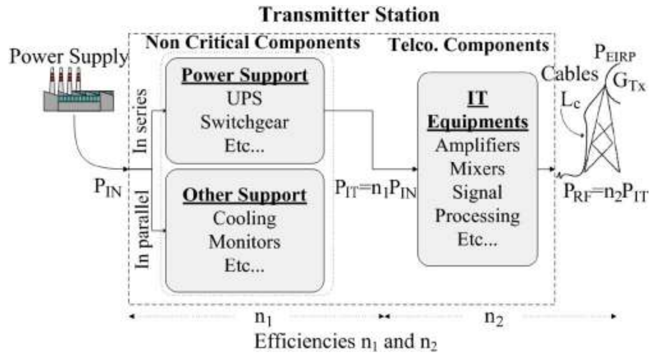

Fig. 2. Power consumption at transmitter.

TABLE I
POWER CONSUMPTION AND RF OUT OF COMMERCIAL DVB TRANSMITTERS

RF out (rms) P_{RF}	Power Consumption P_{IN}	Transmitter Type (Type)
20W	500W	1
80W	1.3KW	1
150W	1.9KW	1
250W	2.5 KW	1
300W	3.7 KW	1
600W	6.1 KW	2
900W	8.1 KW	2
1.2KW	12.1 KW	2
1.8KW	16.1 KW	2
2.4KW	24.1 KW	2

A. Energy Consumption

The research towards a low energy network operation has attracted a lot of interest. The power consumption of telecommunication networks can be divided into three categories, the operation costs, the computation costs and the communication costs. Operation costs refer to inefficient power consumption (high electricity demands) by the transmitting stations. Computation costs are associated to data processing and communication costs are caused by redundant data transfer. Based on these observations, energy efficiency in telecommunication networks can be generally described by a five step process. Optimized planning and dimensioning, efficient electronic equipment, penetration of renewable energy sources, advanced cooling techniques and proper protocol design [6].

Transmitting stations in broadcast systems and base stations in cellular systems suffer of great energy inefficiencies. Similar to the datacenter operation [6], [24], the telecommunication equipment (telco) is coupled to non critical components that provide the operational support to it. Energy is wasted for the operation of the non critical equipment (cooling) and by inefficient electronic and telecommunication equipment (power amplifiers, signal processing units, etc...). An example is presented in Fig. 2. The power from the electricity grid network or the power supply unit is divided to a 'in series' path to the telco equipment and to an 'in parallel' path. The P_{IT} is necessary for the operation of the telecommunication equipment. These provide the required $\mathrm{P_{RF}}$ (rf out) to the transmitting antenna for data delivery. In general, the main causes of energy waste in such systems are the cooling and high power amplifiers. Two efficiency metrics are distinguished i.e.

$$n_1 = \frac{P_{IT}}{P_{IN}} < 1, \quad n_2 = \frac{P_{RF}}{P_{IT}} < 1$$

The efficiency index n_1 mainly depends on the cooling system and the power units. On the other hand, the efficiency metric n_2 depends on the operation of inefficient amplifiers, signal processing units, cable losses and protocol design (coding rate, modulation scheme, etc...). The efficiency metrics are not constant with time but they also depend on the workload and the environment. The most important elements that provide energy efficiency within the stations are freecooling techniques, pre distortion A-Doherty power amplifiers, thermal tolerance of electronic equipment and efficient design of the physical layer (modulation, coding rate, etc...) [6], [25]–[29].

From Fig. 2 it can be observed that for an antenna with gain G_{Tx}, cable losses L_C to transmit a power P_{EIRP}, the required power consumption of the station is

$$\begin{aligned} P_{EIRP} &= \frac{P_{RF}G_{Tx}}{L_c} \\ P_{IN} &= \frac{1}{n_1 n_2} P_{RF} \\ P_{IN} &= \frac{1}{n_1 n_2} \frac{P_{EIRP}L_c}{G_{Tx}} \end{aligned} \tag{5}$$

Tabulated values representing the relationship between the rms RF out (P_{RF}) and power consumption (P_{IN}) of commercial DVB transmitters are shown in Table I [30] (the transmitter type field is described in the next section).

B. Carbon Emissions

The carbon footprint of a transmitting station depends on its power consumption and on the origin of the electricity production. In order to provide a measure of carbon emissions, the energy is converted to gr of $\mathrm{CO_2}$. This is subject to each country energy sources. The relationship is $Q = 1KWh \sim XgrCO_2$. For anthracite electricity production $X = 870$ and for gas electricity production $X = 370$ [31]. The used metric is $\mathrm{TonsCO_2/year}$. Therefore, the carbon footprint of transmitter i of the network is computed according to

$$K_i^{CO_2} = 8.64 \cdot 10^{-6} \cdot P_i^{IN} \cdot X[TonsCO_2/year] \tag{6}$$

where P_{IN} is expressed in *Watts* and X in $grCO_2$. Carbon emissions are also caused to the site visits. Site visits is the number of the required visits to the station, annually, for maintenance purposes. Assuming that F is the number of visits per year, $D(\mathrm{Km})$ is the road distance from the maintenance (engineer) station to the transmitter (see Fig. 3), the site visits are independent for each transmitter and the car produces $C = 1\,Km \sim Y grCO_2$, the carbon footprint is

$$E_i^{CO_2} = 2 \cdot 10^{-6} \cdot D_i \cdot F \cdot Y[TonsCO_2/year] \tag{7}$$

A common diesel car produces around $225grCO_2/Km$ $(\mathrm{Y} = 225)$. The total emissions for transmitter i is then equal to

$$Tx_i^{CO_2} = K_i^{CO_2} + E_i^{CO_2}[TonsCO_2/year] \tag{8}$$

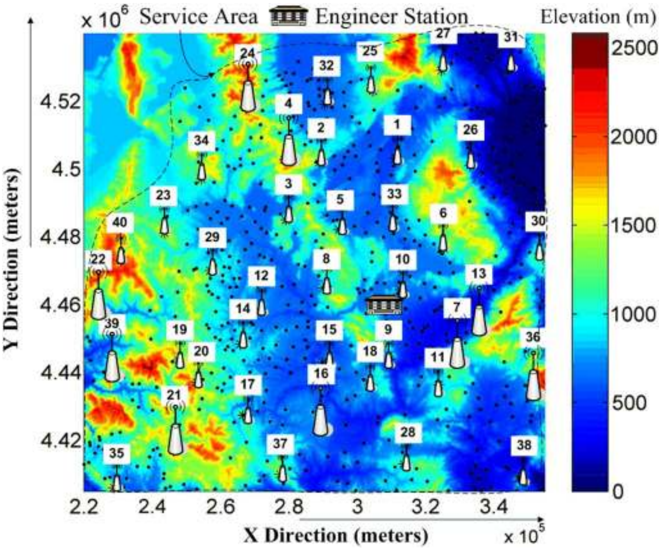

Fig. 3. DTEM with possible transmitter sites, central engineering station for site visits and receiving points.

C. Exposure to Radiation or Radiation Pollution

The exposure to radiation is computed according to the safety index (SI) or exposure coefficient indicated by the EU [8]. The SI is computed whenever there is exposure of humans to sources of radiation. SI is defined as the sum of the ratios of the computed power density at every frequency for a given receiver position over the threshold value. In many countries, like in Greece, the maximum threshold value is 60% of the threshold value indicated by the EU. This value is computed according to (for the frequency range between 400–2000 MHz)

$$S_{f_i}^{\lim it}(W/m^2) = 0.6\frac{f_i(MHz)}{200}(W/m^2)$$

The SI for a given receiving point caused by a transmitter, j, operating at frequency f_i is given by

$$SI_{jf_i} = \frac{S_{jf_i}(W/m^2)}{S_{jf_i}^{\lim it}(W/m^2)} \tag{9}$$

For the purpose of our investigation, the transmitters are operating at $f_i = 600$ MHz. The total exposure at a given receiving location caused by N transmitters equals

$$SI_{total} = \sum_{j=1}^{N} SI_j \tag{10}$$

IV. GREEN DEPLOYMENT AND OPTIMIZATION PROBLEM

This section describes the network planning procedure formulated as a discrete optimization problem. The concept of green deployment is investigated and the objective functions of the problem are also discussed.

A. Decision Variables

The SFN incorporates 40 possible transmitter locations (see Fig. 3) that are defined by a set of geographical coordinates. Twenty already used transmitters and 20 additional sites are assumed as possible locations. Each site can occupy at maximum one transmitter and can have an emitted power and antenna height that depends on its type and location (see Table I). The receivers are defined by 600 residential areas determined by local authorities.

$$Tx_i \rightarrow N = \{x_i, y_i\},\ i \in [1 \quad N]$$
$$Rx_i \rightarrow M = \{x_i, y_i\},\ j \in [1 \quad M]$$

where N $= 40$ and M $= 600$. For the purpose of our investigation the following sets are distinguished

$$T\{4,7,13,16,21,22,24,36,39\} \rightarrow T \subset N$$
$$G \rightarrow G \subset N,\ G \notin T$$

According to these sets two types of transmitters exist (see Table I).

$$Tx_i^{Type} = 1,\ i \in G$$
$$Tx_i^{Type} = 2,\ i \in T$$

Type1 transmitters are allowed to have antenna height of 30m and RF output levels shown in Table I. These sets are named as H_1 and P_1. *Type2* transmitter sites can have either 30m or 80m antenna height and power levels shown in Table I. These sets are named as H_2 and P_2.

The decision variables of the problem with respect to transmitter site (x_i, y_i) are

$a_i \in \{0,1\}$	a_i is an on-off parameter indicating if a transmitter exists at the specific location or not
$p_i \in \begin{cases} P_1, & i \in G \\ P_2, & i \in T \end{cases}$	p_i is a set of available power levels (rf out). It is meaningful only if $a_i = 1$. p_i is translated to EIRP according to (5)
$h_i \in \begin{cases} H_1\{30\}, & i \in G \\ H_2\{30,80\}, & i \in T \end{cases}$	h_i is a set of available antenna heights. It is meaningful only if $a_i = 1$.

During the optimization process feasible network configurations create a set $S \subseteq N$ that contains vectors $\boldsymbol{a}, \boldsymbol{p}, \boldsymbol{h}$.

B. Design Constraints

The network configuration must satisfy one constraint, i.e., that the coverage probability at the reception points must be equal or greater than the imposed by the network services, threshold value (4). Let the set $Z \subseteq M$ describe the receiving points that satisfy the constraints.

C. Objective Functions

In order to provide a comparison of the "green footprint" between various planning strategies the following objective functions are distinguished:

Coverage Optimization (CO): The objective function at this strategy is formulated to minimize the percentage of receiving points where the coverage probability constraint (4) is not satisfied. In a mathematical form this is described

$$CO = \max\left[\Pr\left\{U(x_i, y_i)\right\} \geq U_o\right], \ i \in Z \tag{11}$$

Transmitter Minimization (MTx): The objective function according to this strategy is formulated to minimize the number of used transmitters required that the coverage constraint is satisfied (4). In a mathematical form this is described

$$MTx = \min \sum_{i \in S} a_i \tag{12}$$

Exposure Minimization (EM): The objective function of this strategy is formulated to minimize the exposure level at the residential areas and satisfy the coverage constraints (4). The scope is to minimize the median value of SI (10) obtained at all the receiving locations. In a mathematical formulation this is described as

$$EM = \min(SI_{total}) = \min\left(median\left[\sum_{j \in Z}\sum_{i \in S} SI_{j,i}\right]\right) \tag{13}$$

Energy Efficiency (EE): An energy efficient network configuration is the network that satisfies the coverage constraints and at the same time consumes the minimum possible energy. The objective function at this strategy is formulated to minimize the total required energy of the network (5). In a mathematical formulation this is described as

$$EE = \min\left(\sum_{i \in S} P_i^{IN}\right) \ [\text{Watts}] \tag{14}$$

If the station efficiencies n_1, n_2 of each transmitter are known, (14) can be formulated in a more generic approach, taking into account (5)

$$EE = \min\left[\sum_{i \in S} \frac{1}{n_{i1} n_{i2}} \frac{a_i p_i^{EIRP}}{G_{Txi}} L_{ci}\right] \ [\text{Watts}] \tag{15}$$

Carbon Footprint (CF): The objective function of this strategy is formulated to minimize the carbon footprint of the network providing a satisfactory coverage percentage (4). Each transmitter of the network configuration is responsible for carbon emissions caused to the electricity consumption (6) and site visits (7). The objective function is formulated as

$$CF = \min \sum_{i \in S} Tx_i^{CO_2}[TonsCO_2/year] \tag{16}$$

In a more generic representation (16) can be written as

$$CF = \min\left[\sum_{i \in S} \frac{1}{n_{i1} n_{i2}} \frac{a_i p_i^{EIRP}}{G_{Txi}} L_{ci} \cdot 8.64 \cdot 10^{-6} \cdot X + \sum_{i \in S} 2 \cdot 10^{-6} D_i \cdot F \cdot Y\right] \tag{17}$$

In the following section it is observed that site visits produce a small amount of carbon emissions compared to the transmitters' electricity consumption and are of minor importance to DVB networks. It can be said that an energy efficient network is a low carbon network.

Green Deployment (GD): The objective function according to this strategy is formulated to produce a sustainable network configuration. Sustainability stands for energy efficiency and low exposure. The constraints of (4) must also be satisfied. A simplified heuristic approach to represent the multi-objective problem in a mathematical form is

$$GD = EE \cdot EM \tag{18}$$

The multiplication of the objective functions provides an optimization that is expected to produce a network configuration with characteristics placed in between the two strategies. This approach accepts an inter-relation of the two strategies EE, EM assuming that the importance of each one is proportional to the value of the other. The inter-relation of the two strategies is observed in the simulation results. Another approach to the multi-objective optimization problem is to assign different weight factors to each strategy taking into account normalization to transform the non-homogeneous quantities and proceed with the sum of the objective functions [16].

The optimization problems are defined in the equation at the bottom of the page.

$$\begin{array}{lll}
produce & CO, MTx, EM, EE, CF, GD & \\
subject\ to & a_i \in \{0, \quad 1\} & \forall i \in S \\
 & p_i \in \begin{cases} P_1, \ i \in G \\ P_2, \ i \in T \end{cases} & \forall i : a_i = 1, \ i \in S \\
 & h_i \in \begin{cases} H_1, \ i \in G \\ H_2, \ i \in T \end{cases} & \forall i : a_i = 1, \ i \in S \\
considering & p_c(x_j, y_j) = \Pr\left\{U(x_j, y_j) \geq U_0\right\} & \forall j \in Z
\end{array}$$

V. GENETIC ALGORITHM OPTIMIZATION TECHNIQUE

The network planning is formulated as a discrete optimization problem. A genetic algorithm technique is developed for this purpose. The main elements of the genetic algorithm (GA) are the genes, the chromosomes that consist of genes and the generation that consists of a population of chromosomes. The gene refers to a single transmitter and has three entries. Parameter a (exist or not a transmitter), parameter p (EIRP of the transmitter) and parameter h (the antenna height). The chromosome is a set of genes and is considered as a possible solution to our problem. The generation comprises a number of chromosomes (population) that participates to the evolution process. The evolution is based on various selection procedures such as *elitism*, *roulette wheel* and *tournament*, each one presenting advantages and disadvantages according to the investigated scenario, followed by crossover and mutation [32]. Five basic steps can be distinguished in the GA optimization process.

A. Initial Population/First Generation

The GA starts the optimization procedure from an initial set of network configurations that are randomly generated. The first population is $\boldsymbol{P^0} = \{\boldsymbol{a^0}, \boldsymbol{p^0}, \boldsymbol{h^0}\}$ where $a^0_{i,k} \leftarrow U_n(0,1)$, $k = 1 \rightarrow 60$, $p^0_{i,k} \leftarrow U_n(P_1)$, $i \in G$ and the height is, $h^0_{i,k} = U_n(H_1)$, $i \in G$ for $Type_1$ transmitters and for $Type_2$ transmitters $p^0_{i,k} \leftarrow U_n(P_2)$, $i \in T$, $h^0_{i,k} = U_n(H_2)$, $i \in T$. U_n denotes uniform independent random samples of the discrete set. A randomly generated initial population is required in order to provide the evolution algorithm a great variety of chromosomes that can produce a 'strong' final generation. The algorithm searches the state space via a series of evolution steps.

B. Fit Function

A fit function is computed for each chromosome of the population and at every generation, representing the optimization target. This function 'weights' the chromosomes of the population in order to distinguish the 'strong' and 'weak' candidates of the future generations.

C. Penalty

The fit function of the chromosomes that do not satisfy the constraints is penalized. This procedure reduces the probability of their participation and transferring of their genes to the next generation. A linear penalty was used

$$\Psi = k \cdot \frac{C_0}{p_c(x_i, y_i)} > 1 \tag{19}$$

where k is a constant value and it was set to $k = 10$, C_0 is the targeted coverage percentage and p_c is the obtained coverage percentage.

D. Crossover/Mating

At this stage the algorithm selects "strong" chromosomes, mates them and produces the next generation of population. A tournament selection algorithm was used that randomly selects 6 chromosomes of the population and the 'strongest' is considered as a candidate of mating. The tournament selection produces an intermediate population and the crossover of these chromosomes produces the next generation. The crossover probability was assumed 90%, otherwise elitism selection distinguishes the "strongest" chromosome and directly passes it to the next generation. A randomly generated, single-point crossover approximation was utilized.

E. Mutation

Mutation is considered as an important step in the evolution process. Mutation occurs to the genes of the chromosome and randomly adjusts their values. The mutation probability was set equal to 0.5% to achieve convergence in less than 100 generations.

At each generation a set of possible network configurations are obtained that consists of the population of chromosomes $\boldsymbol{P^g} = \{\boldsymbol{a^g}, \boldsymbol{p^g}, \boldsymbol{h^g}\}$, where g is the generation number. A maximum number of 100 generations were examined. GA do not converge to a global minimum, but instead it provides a set of optimized network configurations. The choice of the final one is subject to further constraints or decisions. For the purpose of our investigation the chromosome with the best fit function was chosen.

VI. NUMERICAL RESULTS

This section presents the scenario under investigation and discusses the results of the network planning strategies. The first discussion, concerns the investigation of the carbon footprint of four different planning strategies named as CO, MTx, EM and EE. The second part compares the above network planning strategies and the GD in terms of their optimized results. The final section investigates the effect of site visits to the total carbon footprint of the network, CF and the carbon footprint for two different electricity production mechanisms, i.e. the electricity production form anthracite and from gas. Finally, the EE and MTx strategies are compared in terms of their sustainability and their cost.

A. Scenario of Interest

The scenario under investigation is presented in Fig. 3. The terrain is modeled by a DTEM with resolution of 90 m and accuracy of 16 m. The effect of the terrain accuracy to final field predictions was computed through a set of 100 randomly generated simulations. An error of maximum magnitude of 16 m was introduced in the DTEM to represent the inaccuracy of the database. It was found that the field variations caused by the 16m accuracy of the database was of the order of 2 dB. This value was introduced to the planning threshold of the algorithm, shown in Table II. The 40 possible transmitter locations and 600 residential areas representing the target area of the delivery of the DVB service are shown in Fig. 3. A DVB-T fixed reception system was assumed, but this can be easily transformed to other services, like DVB portable or even DVB-H, by adjusting the necessary parameters of the network. The desired parameters of the network are presented in Table II. The field computations were performed by the multi-shape slope UTD technique. This technique utilizes the *'stretched string'* algorithm to distinguish the main obstacles in a given terrain profile and the multi-shape slope UTD solution is applied to model the terrain irregularities by a cascade of best fitted canonical obstructions (cylinders, wedges, knife edges) [22]. The terrain profile from the given

TABLE II
DVB NETWORK AND PLANNING PARAMETERS

DVB Parameters	SFN
Modulation	64-QAM
Code Rate	2/3
Guard Interval (T_{GI})	¼ (224μsec)
Interval of correct equalization (T_f)	$2T_{GI}$
Mode	8K
Bit Rate	19.91Mbps
Minimum C/I for fixed reception (Rician Channel) U_0	17.1dB
Location Variation (std)	5.5dB
Max. distance without interference d (T_{GI})	67.2Km

Planning Parameters	Value
Frequency	600MHz
Bandwidth	7.6MHz
Receiver Noise Figure	5dB
Feeder Loss	3dB
Transmitter Cable Loss	3dB
Antenna Gains (Tx, Rx)	10dB
Rx Height for DVB	10m
Rx Height for SI computation	1.5m
Rx effective aperture (Aeff)	0.631
DTEM accuracy safety value	2dB

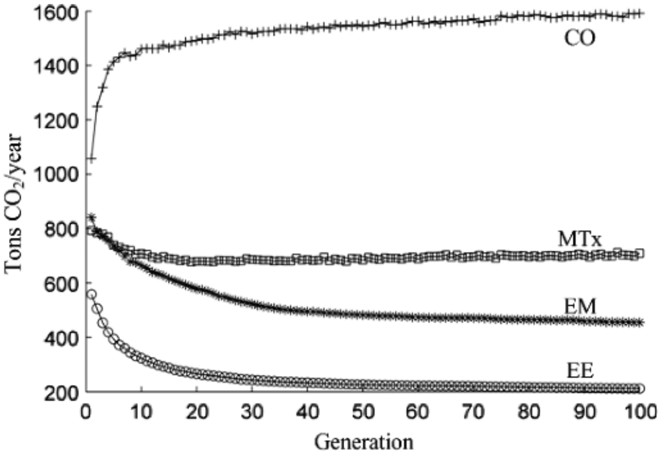

Fig. 4. Carbon footprint of CO, MTx, EM *and* EE planning strategies.

DTEM and Tx and Rx points was extracted by employing a bi-cubic spline interpolation algorithm that has been proven to work with acceptable accuracy in 3D terrain maps [33]. Comparison between the used propagation model and real measurements show a very good fit [22].

B. Optimization Behavior in Terms of Carbon Footprint

The scope of this investigation is to observe the carbon footprint variation of the network during the optimization process. The simulation results were obtained by the mean values of the carbon emissions, at each generation, over 100 independent runs (see Fig. 4). At each generation the chromosome with the best fit function (according to the optimization target) was chosen and the carbon emissions of the specific network configuration were computed. It can be observed that the CO optimization target deploys a network with the maximum carbon footprint. This is because more transmitters are required at higher emitted power levels to produce a high coverage probability. The coverage was optimized to a mean value of 96% instead of the 85% required by the DVB service. The MTx optimization strategy produced a slight decrease of the carbon emissions compared to the randomly generated initial population. Compared to CO strategy, the MTx reduced the carbon emissions and this is expected since the coverage percentage was 85% instead of 96%. On the other hand the carbon footprint of this strategy is greater than EM and EE. The reason is that for the MTx case the obtained network configuration consists of less transmitters operating at high power levels. This is also explained in the following section. The EM optimization strategy produces a low carbon network configuration but not an optimum one. EM and EE follow a similar behavior because both strategies require a greater number of transmitters operating at lower power levels. The EE strategy produced a minimum carbon footprint network and it is shown that the difference of EE compared to MTx and CO strategies is of the order of 550 and $1300\text{TonsCO}_2/\text{year}$ respectively.

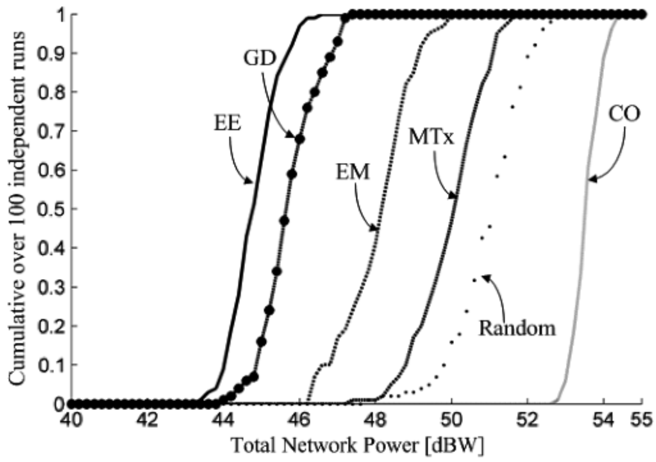

Fig. 5. Comparison of the total energy consumption.

C. Comparison of Planning Strategies

The scope of this investigation is to observe and compare the network configuration characteristics at the final generation of the GA (optimized results). The examined parameters are the total power consumption, the required number of transmitters and the safety index for the planning strategies of CO, MTx, EM, GD, and EE. For comparison reasons a randomly generated network configuration, that satisfies coverage criteria, is also presented (*random*). Fig. 5 presents the comparison in terms of total required network power. It is observed that the EE strategy produces the most energy efficient network. This means that with the minimum possible total energy consumption the delivery of DVB services is achieved. Another important observation is that EM strategy produces an energy efficient network compared to the random and MTx scenario. The GD strategy which targets to a minimization of both energy demands and exposure to radiation, obtains an energy efficient network but not an optimum one. This is because the safety index is also considered into the fit function. The MTx strategy presents

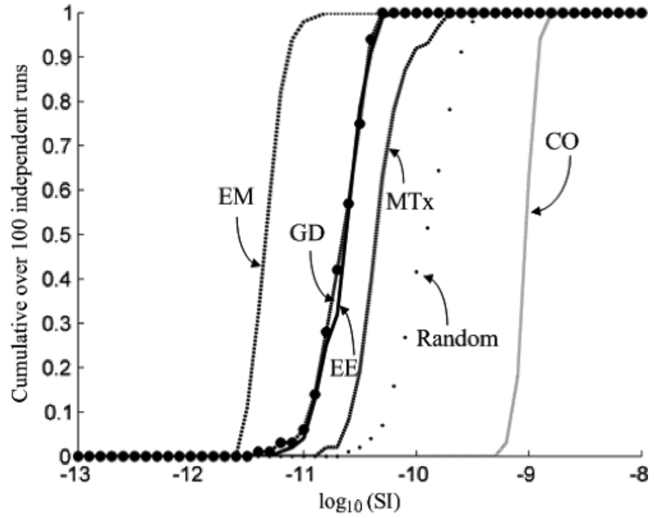

Fig. 6. Comparison of the generated exposure to radiation.

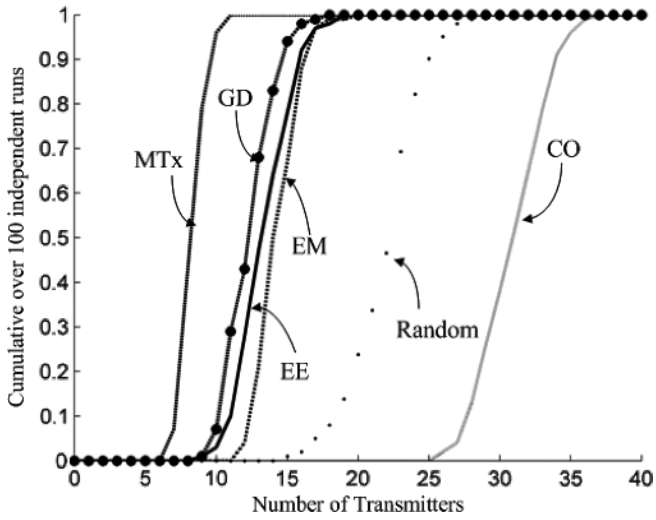

Fig. 7. Comparison of the required number of transmitters.

less energy demands compared to the random case. Finally, the CO requires huge amount of energy to achieve the optimization goal of maximum coverage. In Fig. 6 the electromagnetic exposure, described by the safety index is presented. It is observed that EM strategy produces the minimum exposure at the receiving locations. The GD strategy produces a network with a slight reduction of the radiation exposure compared to EE. The GD scenario minimizes the product of EE and EM and as a consequence the results of GD lie in between the two strategies. The reason that the GD has a smaller difference with EE in terms of SI compared to the power requirements, (see Fig. 5), is that the reception points have a certain distance from the transmitting locations and the field has already been attenuated by obstructions and free space loss. The MTx scenario produced a network with less exposure than *random* generated networks and CO networks presented the highest radiation pollution and exposure. The final comparison was focused on the number of transmitters required by each strategy (see Fig. 7). The MTx scenario produces a network configuration with the minimum number of transmitter sites that operate at high power levels. On the other hand GD, EE and EM required almost the same number of transmitters (mean difference of the order of 1). *Random* network configurations and CO requires the highest number of transmitters. It can be concluded that the EE and EM planning strategies have similar behaviors in terms of energy consumption and exposure and they always present more sustainable results compared to the MTx. It was shown that for real planning scenarios, EE is of most importance since the gain in terms of energy consumption is higher than the gain of SI reduction achieved by the GD. The GD strategy produced a median solution but again the obtained gains were higher for EE. In addition, the MTx had always a more sustainable behavior than the randomly generated networks. Finally, when coverage optimization is targeted (CO) the price to be paid is high exposure to radiation and energy waste.

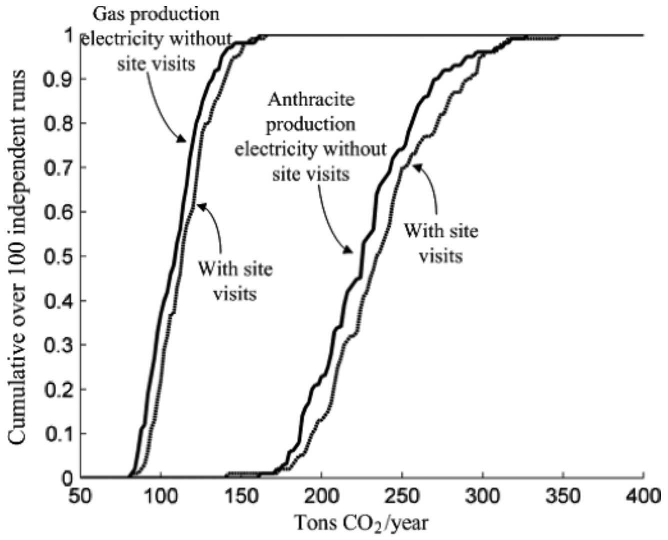

Fig. 8. CF simulation results for two different cases. A gas oriented and anthracite oriented electricity productions are examined resulting to $\mathrm{X} = 370\mathrm{grCO_2/KWh}$ and $X = 870\mathrm{grCO_2/KWh}$ respectively. Site visits were also considered with a frequency of $\mathrm{F} = 12$ site visits per year with a common car producing $\mathrm{Y} = 225\mathrm{grCO_2/Km}$. X, Y, F are defined in (6) and (7).

The planning of the network should be carefully designed together with accurate propagation models, realistic scenarios of interest and carefully predefined quality of service and coverage probabilities. The provision of high coverage probabilities at non residential areas implies a great cost for the sustainable operation of the network.

D. Further Comparisons

This section investigates the carbon footprint of two different scenarios. The first concerns the CF optimization strategy for gas and anthracite electricity production schemes assuming zero site visits per year and 12 site visits per year. The results are plotted in Fig. 8. It can be observed that there is a great reduction of the carbon footprint of the network when electricity is generated by gas. Furthermore, it can be observed that the effect of site visits (assuming a realistic value of 12 site visits per year) is small compared to the carbon emissions due to the operation of the transmitters. An investigation of the effect of site visits according to the frequency of site visits (F) and type of electricity production (X) showed that carbon emissions due to site visits

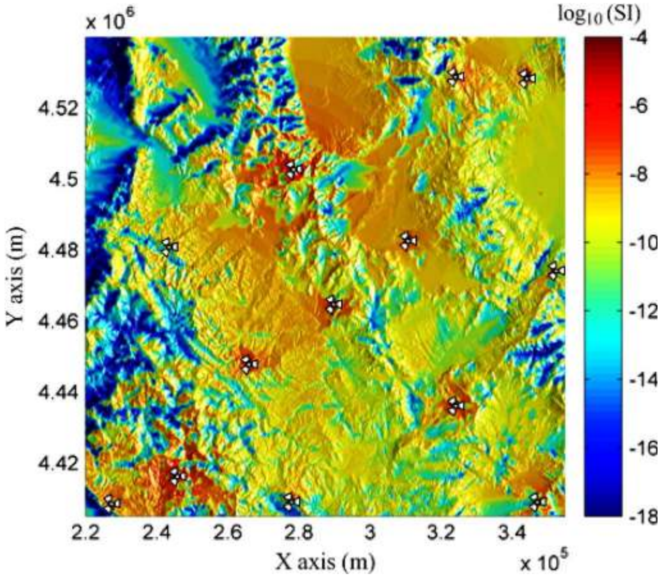

Fig. 9. Safety index variations for mean (EE) network (Table III).

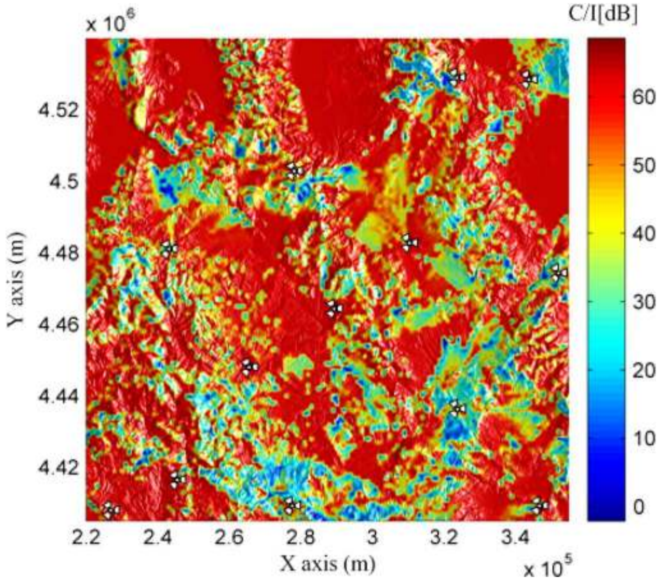

Fig. 10. C/I for $\mathrm{T_{GI}} = 224\ \mu\mathrm{sec}$ (1/4) for mean(EE) network (Table III).

(E^{CO2}) can be comparable to carbon emissions due to the operation of the transmitters (K^{CO2}) when $\mathrm{F/X} > 0.1$. Assuming a gas oriented electricity network $(X = 370gr\ CO_2/year)$ the number of site visits required to make E^{CO2} comparable to K^{CO2} was found to be $F = 37$ site visits per year, that is not met in real scenarios. Of course, for cellular mobile networks, where the network configuration consists of a large number of transmitters, this conclusion requires further investigation.

Fig. 9 presents the SI map obtained by the network configuration that corresponds to the mean(EE) optimization strategy. For the same network configuration the carrier to interference map assuming a 224 $\mu\mathrm{sec}$ $\mathrm{T_{GI}}$ (see Fig. 10) is also presented. The first observation (see Fig. 9) is that the exposure to radiation decreases for reception points placed away from the transmitters. The effect of the terrain obstruction is also clear. On the other hand, there are some areas that present increased exposure due to the unobstructed reception of signals from multiple stations. In Fig. 10 the C/I map (neglecting thermal noise) is presented and the effect of the guard interval is observed. It was found that for a guard interval of $\mathrm{T_{GI}} = 112\ \mu\mathrm{sec}$ (1/8) the reception was interference limited.

TABLE III
NETWORK CONFIGURATIONS FOR EE AND MTx

Energy Efficient Network Configuration (*EE*)
Power Consumption 44.56dBW, Required Transmitters 13

Site id	EIRP[dBW]/Height [m]	Site id	EIRP[dBW]/Height[m]
4	36.5/80	30	20/30
8	26/30	31	20/30
11	26/30	33	20/30
14	26/30	35	20/30
21	36.5/80	37	20/30
23	20/30	38	26/30
27	26/30		

Min Tx Network Configuration (*MTx*)
Power Consumption 49.78dBW, Required Transmitters 7

Site id	EIRP[dBW]/Height[m]	Site id	EIRP[dBW]/Height[m]
4	40.8/80	30	34.7/30
7	40.8/80	31	34.7/30
20	34.7/30	37	34.7/30
21	39.5/80		

Sustainability Comparisons (assuming 870grCO_2/KWh, 0.1€/KWh)

Scenario	CO_2[Tons/Year]	Electricity OPEX[K€/Year]	Exposure [$\log_{10}$(SI)]
EE	214	24.69	-10.4[dB]
MTx	714	82.132	-10.86[dB]
Savings	500	54.42	0.46[dB]

Table III compares the network configurations that correspond to mean(EE) (same of Fig. 9) and mean(MTx) case. Following the same observations with section B, C, it is shown that the EE optimization strategy produces a network that consists of a greater number of transmitters operating at lower power levels, whereas the MTx strategy presents opposite behavior. This can also provide the necessary foundations for the penetration of renewable energy sources (RES) into the network. The limited energy supply of RES requires the transmitters to operate at low power levels. Regarding the sustainability parameters and costs of these networks it can be observed that when energy efficiency is introduced to the planning strategy, $500\mathrm{TonsCO_2/year}$ and 54420 euro/year can be saved compared to the minimum transmitter planning strategy. Finally a decrease of 0.46dB of the exposure index SI is also observed. The effect of the prediscussed results becomes greater when the network deployment concerns a whole country.

VII. CONCLUSION

This paper explored the green deployment of single frequency networks and focused on DVB-T services. For the purpose of the investigation a GA optimization technique was developed and field predictions over the DTEM were based on the multi-shape

UTD approach. Various optimization strategies were compared in terms of their sustainable deployment. It was shown that when energy efficiency, low carbon emissions and low exposure was targeted and was introduced as the objective functions to the optimization, great sustainable goals can be achieved. Specifically, it was shown that for SFNs the energy efficiency optimization strategy created a low carbon and a low exposure network configuration compared to coverage optimized and minimum transmitter strategies. In addition, this provides the required foundations for the penetration of renewable energy sources into the network and follows the guidelines for 20% reduction of energy demands by 2020. Finally, the effect of site visits to carbon emissions proved to be of minor importance for broadcast networks. The future plan of this research is to examine the green deployment of next generation cellular mobile networks.

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