Finding repeater placement for P2P wireless links with NLOS in extremely mountainous regions

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***Abstract*— A backhaul network consisting of p2p microwave links is the most cost-effective solution for rural Internet access, however, it can be a challenging design because the extreme mountainous geographical conditions make the links have Non-line out sight (NLOS) and be necessary the use of repeaters. Many relays can be implemented to overcome this difficulty. To the best of my knowledge, it does not exist an approach to finding the suboptimal repeaters placement in a computational way. This paper proposes the form to construct a cost function that represents the problem described before, and a genetic algorithm is implemented to find its local minimum at different scenarios.**

***Keywords*— Wireless backhaul network, rural zones, repeaters placement, digital elevation map.**

I. INTRODUCTION

Developed and undeveloped countries are concerned about providing Internet in rural zones [1]–[3]. In this kind of scenarios, a traditional optical fiber backhaul network is too costly [4], also the required installation routes are long and intricate, and some sites may be very difficult to reach. For this reason, wireless alternatives are implemented. Many approaches to the wireless backhaul for rural Internet access have been proposed. Most of them use point to point radio (p2p) links based on WiFi [5]–[7], WiMAX [8], or proprietary technologies [9]. These works concentrate on describing specific implemented solutions, but they do not address the network design problems, nor optimization procedures. In [10] a tool for incremental planning of wireless networks is presented, but is limited to network expansion rather than initial design. Other solutions for rural scenarios are mesh networks, which can be implemented with WiFi or WiMAX stardards [11]–[13], and Satellite options can be considered as well.

In rural scenarios is difficult to design wireless backhaul networks because line of sight (LOS) between nodes is not always achievable. LOS is reached in a radio link if there are no obstacles in the straight line between the antenna sites and the first Fresnel zone is cleared. Most of WiFi-based p2p links work in the 5 GHz U-NII bands in order to avoid interference at 2.4 GHz, and to take advantage of a smaller Fresnel zone clearance. In practice higher towers are used at the link endpoints to obtain the first zone clearance. However, it can be a challenge because the extreme mountainous geographical conditions (i.e., extremely hilly terrain characterized by strong changes in terrain height over small areas) make the links have Non-line out sight (NLOS) and be necessary the use of repeaters. Many relays can be implemented to overcome this difficulty.

The designer has to be concerned about in finding the repeaters placement such that minimize: relays number, tower heights and links distances. To the best of my knowledge, it does not exist an approach to find the repeaters placement in a computational way. This paper proposes the form to construct a cost function that represents the problem described before. A digital elevation map is used to simulate the rural scenarios. Clearly this problem cannot be solved deterministically. In adition, the complexity of this problem is proportional to $n_c!$, where n_c represents the number of cadidate positions of repeaters, it is discussed with more detail in the Section III, therefore, with the aim to find a suitable solution a heuristic method is implemented in different scenarios. The most popular heuristic to resolves NP-hard problems is the Genetic Algorithm (GA), for that reason it was chosen to deal this problem [14].

The remainder of this paper is organized as follows: Section II describes a criterion to establish if a link is feasible or not; Section III presents my approach to find the suboptimal repeaters placement; Section IV contains numerical results at different scenarios; and finally, in Section V appropriate conclusions wrap up this paper.

II. CRITERION OF LINK FEASIBILITY

Link feasibility can be approached in terms of antenna types, gain, opening angle, etc., however, it can be addressed in a simpler way. For establishing the link connectivity, a criterion of LOS is described in the subsection II-A. On the other hand, the wireless link performance is related directly by the received signal power, therefore, in order to increase this power, the link distance has to be decreased, thus a distance constraint is defined in the subsection II-B.

A. Criterion of LOS

LOS is reached in a radio link if there are no obstacles in the straight line between the antenna sites and the first Fresnel zone is cleared as stated before. In practice higher towers are used at the link endpoints to obtain the first zone clearance. The general equation for calculating the Fresnel zone radius at any point P in between the endpoints of the link is the following:

$$F_n(P) = \sqrt{\frac{n\lambda d_{1-P} d_{P-2}}{d_{1-P} + d_{P-2}}} \tag{1}$$

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Algorithm 1 Searching towers heights to obtain LOS using a finite set of tower heights available

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towersheights function
    Inputs: n_1, n_2, M
    Output: h_{n_1}, h_{n_2}.
starting O = ∅
p = elevationprofile(n_1, n_2, M)
Compute f ∈ R^{n_p}, f_k = F_1(k), k = 1, ..., n_p
for i = 1, ..., m
    for j = 1, ..., m
        l = straight line connecting p_1 + h_i and p_{n_p} + h_j
        c = l − f
        if c_k > p_k, k = 1, ..., n_p
            O = O ∪ [h_i, h_j]
        end
    end
end
if O = ∅
    [h_{n_1}, h_{n_2}] = [10^3, 10^3]
else
    [h_{n_1}, h_{n_2}] = arg min_{h_i,h_j ∈ O} (h_i + h_j)
end
return h_{n_1}, h_{n_2}
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where $F_n(P)$ is the n-th Fresnel zone radius, d_{1-P} is the distance of one end from P, d_{P-2} is the distance of P from the other end, and λ is the wavelength of the transmitted signal.

Let h_{n_1} and h_{n_2} be the towers heights at the link endpoints such that LOS is reached. To limit the search of these values a finite set of tower heights available $\mathcal{H} = \{h_1, h_2, ..., h_m\}$ is defined and the best option from it is found thought exploring brute force.

Algorithm 1 presents a way to find h_{n_1} and h_{n_2} values through the description of the *towersheights* function, which depends on both (*i*) the link endpoints, $\mathbf{n_i} \in \mathbb{R}^2$, $i = 1, 2$, that are given by its corresponding latitude and longitude; and (*ii*) the digital map $\mathbf{M}$ [15], such as the one presented in the Figure 1. At the beginning of the algorithm a set of candidate heights of towers, $\mathcal{O}$, is defined as an empty set. Then, the *elevationprofile* function extracts the elevation profile, $\mathbf{p} \in \mathbb{R}^{n_p}$, between the endpoints, $\mathbf{n_1}$ and $\mathbf{n_2}$, from the digital map $\mathbf{M}$, i.e., this function extracts the heights on a straight line connecting $\mathbf{n_1}$ and $\mathbf{n_2}$ from $\mathbf{M}$. n_p is the number of heights samples in this straight line. We compute the first Fresnel zone radius at all points between the link endpoints according to (1) and we array a vector $\mathbf{f} \in \mathbb{R}^{n_p}$ with theses values. We generate the different straight lines, $\mathbf{l} \in \mathbb{R}^{n_p}$, such that connects the heights of link endpoints plus his respectively height tower using $\mathcal{H}$. If the curve, $\mathbf{c} = \mathbf{l} - \mathbf{f}$, is greater than the elevation profile, $\mathbf{p}$, then we update $\mathcal{O}$ adding the new candidate heights of towers. Finally, we select the couple of towers heights such that sum between them be minimum. If the set of candidate heights of towers is empty we chose an value to h_{n_1} and h_{n_2} absurdly high, thus, when it comes time to perform the optimization this going to help us to avoid repeaters positions with NLOS.

Figure 2 presents the elevation profile of a link with LOS and NLOS using the Algorithm 1.

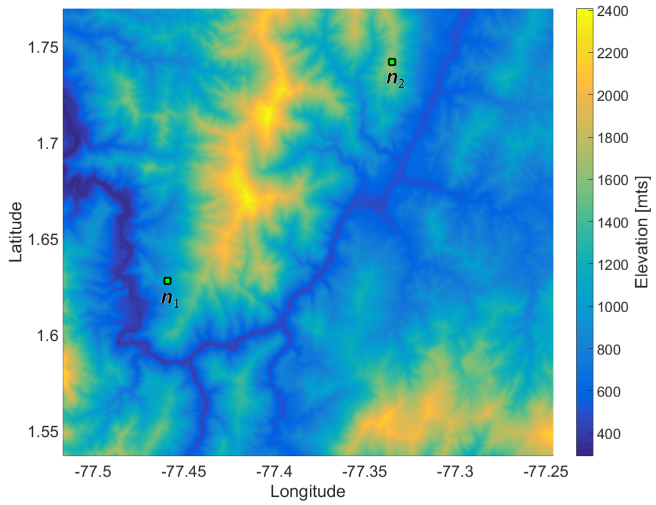


Fig. 1: A scenario for backhaul network design in Nariño, Colombia. Altitude over the sea level (in meters) is represented by colors, showing the tremendous terrain elevation changes and the difficult for designing p2p links.

B. Distance constraint

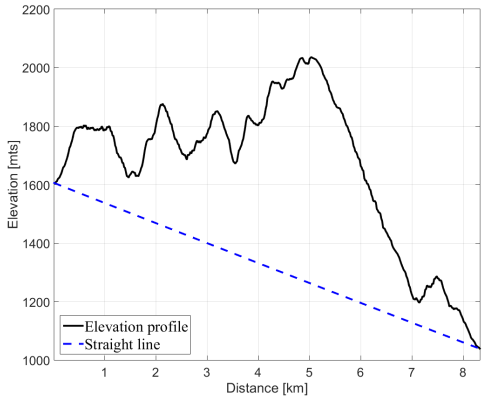
Another important constraint in designing wireless backhaul networks is link distance because the following reasons:

- The free-path loss is proportional to the square of distance and the communication quality depends directly on the received signal power.
- The access points used in p2p links cannot operate with high transmit power due to the constraint hardware and the policies of use of radio spectrum frequency.
- The alignment of the higher directivity antennas at long distance can be difficult to reach.
- In order to decrease the search space.

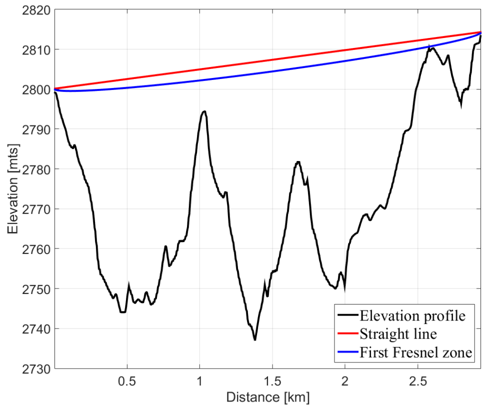
Using the link distance constraint, d_{max}, is possible limits the search space of the repeaters position to an elliptic region. Consider the geometry of an ellipse shown at the Figure 3 and an unfeasible link that just needs a repeater to obtain connection between the endspoints, $\mathbf{n}1$ and $\mathbf{n}_2$. Taking the link endpoints as the ellipse focus, we can obtain the following relations:

- $\mathbf{fe}_i = \mathbf{n}_i$, $i = 1, 2$
- $\mathbf{r}$ = repeater position
- $d_{max} = c + a$
- $d_c = d_1 + d_2$

It lets define the points at the ellipse zone as a set of candidate positions of repeaters, $\mathcal{C} = \{\mathbf{c}_1, \mathbf{c}_2, ..., \mathbf{c}_{n_c}\}$. For the cases where more than one repeater are needed, we use the next approximation to construct the elliptical constraint, $d_c \approx (n_r + 1)d_{max}$, where the n_r is the repeater number to be found.



(a) Link with NLOS



(b) link with LOS, $h_{n_1} = 1$ and $h_{n_2} = 1$

Fig. 2: Elevation profile of links with NLOS and LOS using the Algorithm 1

III. Design of the problem function

A backhaul network consistent of p2p microwave links is the most cost-effective solution for rural Internet access as stated before. This section describes a design methodology for such network in mountainous regions, motivated by the need of many developing countries. Subsection III-A is dedicated to detail the construction of the cost function and the implemented heuristic method is described in the Subsection III-B.

A. Cost function construction

Consider two nodes, $\mathbf{n}_1$ and $\mathbf{n}_2$, be the endpoints of an unfeasible link in a rural scenario, which is defined by a digital map $\mathbf{M}$ [15] (see Figura 1) . Algorithm 2 describes the cost function which takes into account own parameters that we want to minimize, link distances and towers heights, for the case of searching of one repeater position, $\mathbf{r}$. Many scenarios causes that the unfeasible link does not realizable with just one repeater, therefore a similar algorithm to Algorithm 2 with more repeaters into account have to be implemented.

Note that if we want to find the optimum repeater position, we have to explore all elements of the set $\mathcal{C}$, i.e., test n_c candidate repeater positions. However, typically we need more than a relay, so, if we consider n_r repeaters to be found, we have to test all combinations of n_r elements into a set of n_c elements times the permutation of n_r, i.e., $\frac{n_c!}{(n_c - n_r)!} n_r!$, which is computationally prohibitive. Therefore, heuristic techniques must be implemented.

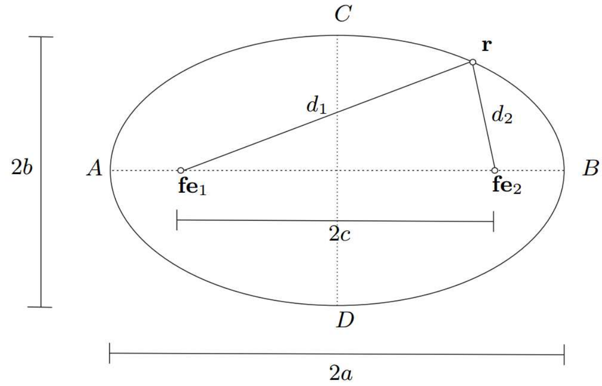


Fig. 3: Geometric of an ellipse

B. Genetic algorithm

Genetic Algorithms are search and optimization techniques inspired by two biological principles namely the process of natural selection and the mechanics of natural genetics. GAs manipulates not just one potential solution to a problem but a collection of potential solutions. This is known as population. The potential solution in the population is called ”chromosomes”. These chromosomes are encoded representations of all the parameters of the solution [14]. Each chromosome is compared to other chromosomes in the population through an awarded fitness rating that indicates how successful a chromosome is. The GA uses genetic operators or evolution operators such as crossover and mutation for the creation of new chromosomes from the existing ones in the population. The selection mechanism for parent chromosomes takes the parent fitness into account. This will ensure that the better solution will have a higher chance to procreate and donate their beneficial characteristic to their off spring. How well an individual performs a task is measured and assessed by the objective function. The objective function assigns to each individual a corresponding value called its fitness. The fitness of each chromosome is assessed and a survival of the fittest strategy is applied [14]. In this project, the cost function described before is the objective function and the element index of the candidate set, $\mathcal{C}$, is taken as chromosome, i.e, each chromosome $\in \{1, 2, ..., n_c\}$.

IV. Numerical results

This section presents some simulations results of the proposed method. All implemented scenarios belong to Nariño-Colombia, because this region belongs to the most mountainous zone in all South America (i.e, the Andes mountains), therefore it gives us a big challenge at the design. The number of repeaters is limited to 2, $N_r = 2$. The frequency transmission is 5 GHz. The set of tower heights available

Algorithm 2 Description of the cost function to a repeater

1: **Inputs**: $\mathbf{r}$
Output: cost
2: Find distances
d_{n_1-r} = distance between $\mathbf{n_1}$ and $\mathbf{r}$ in km
d_{r-n_2} = distance between $\mathbf{r}$ and $\mathbf{n_2}$ in km
$D_{total} = d_{n_1-r} + d_{r-n_2}$
3: Find towers heights
$[h_{n_1}, h_{r1}]$ = *towersheights*($\mathbf{n}_1$, $\mathbf{r}$, $\mathbf{M}$)
$[h_{r2}, h_{n_2}]$ = *towersheights*($\mathbf{r}$, $\mathbf{n_2}$, $\mathbf{M}$)
h_r = the largest elements taken from h_{r1} or h_{r2}
$H_{total} = h_{n_1} + h_r + h_{n_2}$
4: Ideal values
D_{ideal} = distance between $\mathbf{n_1}$ and $\mathbf{n_1}$ in km.
$H_{ideal} = 0$
5: Cost value function
$cost = \sqrt{(D_{total} - D_{ideal})^2 + (H_{total} - H_{ideal})^2}$

is $\mathcal{H} = \{0, 1, 2, ..., 10\}$. Table I resumes the main settings parameters of the GA to the two objective functions.

TABLE I: GA's main settings to searching of

	a repeater	two repeaters
Population size	50	150
CrossoverFraction	0.7	0.7
Generations	1000	3000
StallGenLimit	10^5	10^5

Figure 4 shows the found solution to the challenging scenario given in the Figure 1, where the blue markets represent the repeaters positions. To this scenario two repeaters were necessary. Another scenario with similar complexity is presented in the Figure 5. From all results is very easy to note that the algorithm searches effectively the shortest route to connect the links endpoints. Table II contains the description of interest points of the above designs in terms of latitude, longitude and needed tower height.

TABLE II: Description of p2p wireless link designs

Interest points		Latitude	Longitude	Tower height
Design 1	$\mathbf{n}_1$	1.6279	-77.4589	8
	$\mathbf{r}_1$	1.7149	-77.4447	1
	$\mathbf{r}_2$	1.7466	-77.3998	1
	$\mathbf{n}_2$	1.7419	-77.335	8
Design 2	$\mathbf{n}_1$	1.2301	-77.2873	1
	$\mathbf{r}_1$	1.2237	-77.3224	1
	$\mathbf{r}_2$	1.2848	-77.2322	1
	$\mathbf{n}_2$	1.3821	-77.1566	1

V. Conclusions

This paper proposes a new and unique method to find the suboptimal repeaters placement to connect rural zones using p2p wireless links in a computational way. In the simulations were chosen some very mountainous scenarios to make the backhaul design challenge.

The results show that the proposed method can give good solutions to make workable an infeasible link; nevertheless, it does not mean that we can obtain the final design through this tool. We must be aware that the digital map just represents an approximation of the real scenario because of its limited resolution (the new data have been released with a 1 arc-second, or about 30 meters [15], which, although it can be improved using interpolation still remain inaccurate) and data acquisition time (many changes could have happened in the interest region e.g., landslides or growth of large trees which are not in the database).

On the other hand, to avoid prohibitive places as private zones or very difficult to reach, we must penalize this points adding a big value at his cost function result or removing them from the set $\mathcal{C}$.

Given that the GA difficultly can reproduce the same results, each execution of the algorithm gives a new possible design, this is very useful since several design alternatives can be obtained and thus, the network designer must select which is the better realizable backhaul from them.

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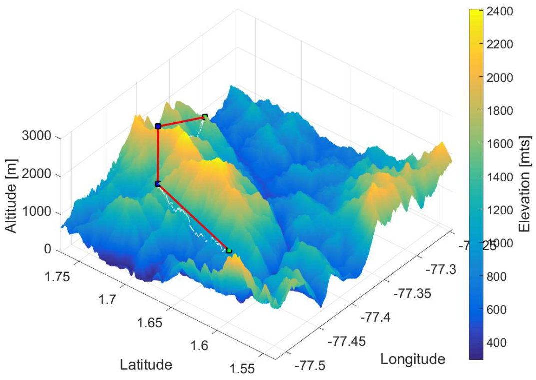
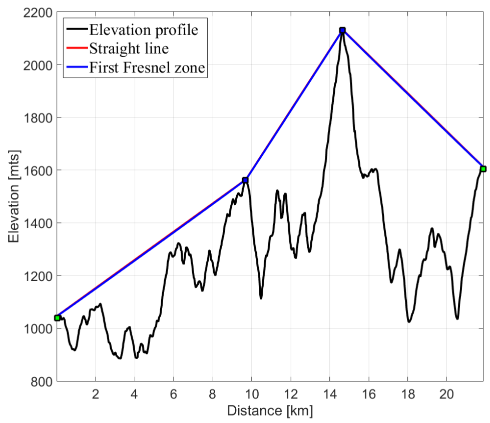
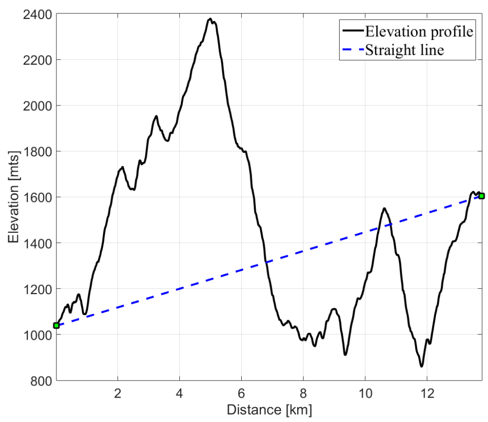


(a) 3D visualization of the wireless links conecction design

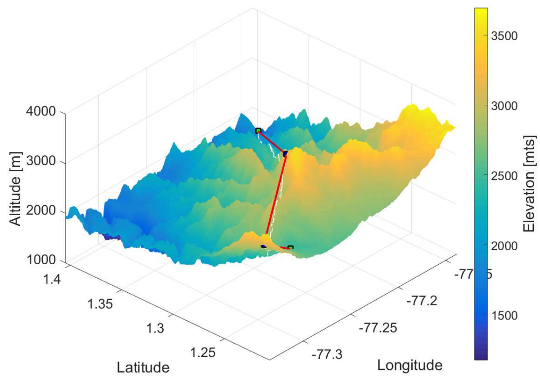


(b) Elevation profile from $\mathbf{n}_1$ to $\mathbf{n}_2$ with relays



(c) Elevation profile from $\mathbf{n}_1$ to $\mathbf{n}_2$ without relays

Fig. 4: Design 1



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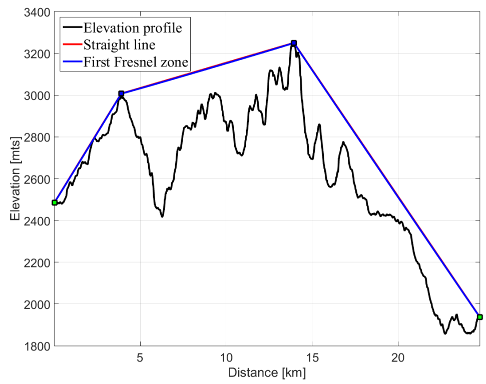
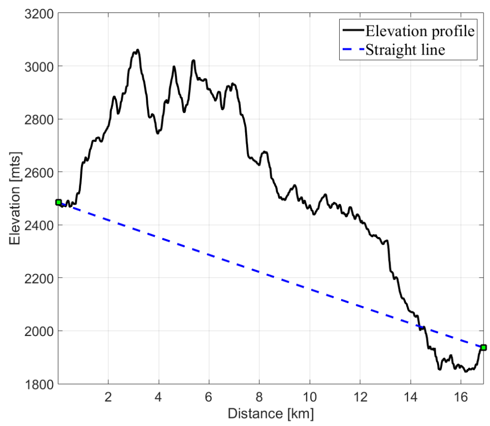


(b) Elevation profile from $\mathbf{n}_1$ to $\mathbf{n}_2$ with relays



(c) Elevation profile from $\mathbf{n}_1$ to $\mathbf{n}_2$ without relays

Fig. 5: Design 2