Planning a Ring-Tree Network to provide Telecommunication Services at Centres of Rural Population

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Abstract: - Nowadays certain centres of rural population are experimenting difficulties to access high-speed telecommunication networks. This phenomenon avoids the possibility of accessing to the digital revolution for such areas. The private companies are focusing their investment efforts in other more profitable areas. In such conditions, the governments have to promote alternatives to bridge the digital divide between rural and urban areas. We present how ring-tree topologies can be used as an adequate architecture to incorporate such less favoured areas in the Information Society. We present a case study for Andalucía (a wide region in the south of Spain) where a decision support system based on a genetic algorithm is implemented providing cost effective solutions. We make use of real life data from the telecommunication industry and present different solutions separated by coverage as well as a sensitivity analysis based on the main factors of the cost function.

Key-Words: - ring-tree network, digital divide, rural population, genetic algorithms, fiber optic, case study

1 Introduction

Nowadays certain centres of rural population are experimenting difficulties to access high-speed telecommunication networks. It supposes a great barrier for its development embedded into the modern digital society. Certainly, the access to information and communication technologies can launch small and medium-sized firms directly into the heart of regional, national and global markets. Also, telemedicine can provide access to up-to-date health and medical information to even the most remote communities. These technologies will facilitate low-cost distance learning. And they can empower civil society, strengthen democratic institutions and make governments more transparent and accountable, [1].

There are not many scientific references dealing with this problem. Although, [2] shows how the use of new information technologies can improve the competitiveness in rural small businesses. However the proposals are in terms of business solutions, but not in terms of communication infrastructure.

Unfortunately, those communities that most need the boost that the technologies of the information and communication can provide are least able to take advantage of it. Because, the Information Society evolution is supported through the telecommunication networks deployment. The high cost of such infrastructures forces the companies to focus their efforts in the profitable communities. To give a solution to it, the governments have to promote alternatives to bridge the digital divide between rural and urban areas. And in many cases these actions must include the funding of new telecommunication infrastructures.

As in other parts of the world, in Spain, the private companies have focused their network extension and modernisation strategic plans on the more profitable communities. It is the case of the big cities of the country. Recently, the Andalusian Regional Government has been leading a series of initiatives aimed at promoting the development of fiber optic networks around the region. And its plan tries to promote the development of such networks, especially, for the less favoured areas.

This objective is the starting point of our work. The General Directorate for the Information Society of the Junta de Andalucía asked us for a tool capable of evaluating the investment volume required to set up a fiber optic network. This network would have to arrive up to the less favoured areas of Andalucía and to connect them to the bigger cities. So our objective was the generation of a tool capable of designing a cost-

efficient backbone network allowing bridging the digital divide and getting access to the less favoured rural zones.

The rest of this paper deals with the identification of the digital divide in Andalucía, and the description of the technological background (respectively in section 2 and 3). Subsequently, we present the model considered to design the network in section 4, and the decision support system based on a genetic algorithm in section 5. The main results are showed in section 6. Finally we finish our paper with the more relevant conclusions.

2 The digital divide in Andalusia

In Europe, the digital divide is a phenomenon that is produced due to the disconnection between the rural and urban communities. It is because the rural areas and its municipalities tend to be non-profitable for the private companies. So the telecommunication networks do not reach those zones.

Recently, the EU Commission Staff working paper, [3], has stated the guidelines on criteria and modalities of implementation of structural funds in support of electronic communications. The working paper shows how the demand aggregation for broadband services should be encouraged in order to ensure critical mass of users in public administrations whilst avoiding dependence on one single operator. Furthermore the stimulation of demand for types or 'clusters' of SMEs allows increasing awareness and use of ICT. The actuations that the working paper states, must be useful to finance content, including e-government, in particular local and regional services in order to boost demand for broadband on a sufficiently focused basis to develop supply. Also the Commission states that the Public authorities, and particularly the Regional authorities (as the case of the Junta de Andalucía is) and local authorities, have a key role to play in the development of the information society by (1) using information society applications and services in the process of modernisation of

services provided to citizens and companies, (2) promoting the information society in the region and (3) monitoring the evolution of the communications networks and services provision on the region in order to avoid exclusion and contribute to the balanced development of regional activities.

In order to attend to these guidelines, we divided Andalucía in three sets. Firstly, we consider as type A municipalities those where exist alternative infrastructure. So, they are cities where a commercial competition is produced (basically between ADSL and coaxial cable). Secondly, we state type B municipalities as those where only exist ADSL but they could have enough service demand to support another telecommunication operator. Finally, type C municipalities are those which has not ADSL infrastructure due to a strong lack of demand.

2.1 Classification of municipalities

There are 18 type A municipalities: Almeria, Algeciras, Cadiz, Chiclana de la Frontera, Jerez de la Frontera, La Línea de la Concepción, El Puerto de Santa Maria, Rota, San Fernando, Sanlucar de Barrameda, Cordoba, Granada, Huelva, Jaen, Malaga, Alcala de Guadaira, Dos Hermanas and Seville. It supposes 43% of the Andalucía entire population (3,164,329 inhabitants).

The population living in type B municipalities is equal to 45% (3,292,609 inhabitants). There are 262 type B municipalities. Furthermore, we divide the type B municipalities between B1 and B2. Type B1 municipalities are those where the existence of another telecommunication operator would be profitable; and B2 municipalities those non-profitable. The separation between B1 and B2 was done considering the expected Payback period, the Net Present Value (NPV) and the Internal Rate of Return (IRR) of each type B municipality. See [4] for an in depth discussion. In order to realize the analysis we considered the initial investment as a function of the municipality size. Basically, we considered the DSLAM cost (including a fixed part and another variable depending on the number of users). As incomes,

we considered the monthly tariff multiplied by the expected demand. The demand was calculated by using different statistical approximation methods (moving average, exponential smoothing, Holt, linear regression and quadratic regression) and minimising the historical error observed by a parametric composition of them. [4] discusses in depth about the demand estimation. As costs, we considered the operation and maintenance costs as a 10% of the incomes (following habitual values from the Industry). Here the possible enlargement of the DSLAM capacities was also included.

Finally, to difference between type B1 and type B2 we selected an IRR upper than 120% and a NPV upper than 3 millions of euros for a 10 years horizon. The result was 43 type B1 municipalities and 219 type B2. The analysis leads to a standard B1 town with 32,500 inhabitants and a standard B2 town with 8,600 inhabitants. The rest of the towns were considered type C. So we manage 490 municipalities that represent the 12% of the entire population of Andalucía, i.e. 883,637 inhabitants.

Figure 1 represents the main characteristics of the municipalities (the demand is expressed as the expected number of "equivalent ADSL lines" for the final period of the horizon). Each "equivalent ADSL line" is considered with a capacity of 256 Kb/s. So, final users with capacities upper than 256 Kb/s are converted in the correspondent number of "equivalent ADSL lines".
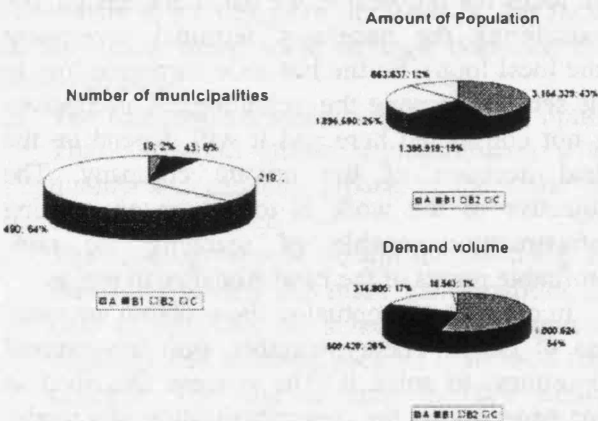

Figure 1. Municipality classification

The number of municipalities in the bad part of the digital divide is 709. It is a population equal to 2,780,327 inhabitants, and most of them are living in rural areas. It represents a great volume of the Andalusian population that will suffer strong difficulties to access to the Information Society and its benefits. Figure 2 details the main characteristics of the digital divide.
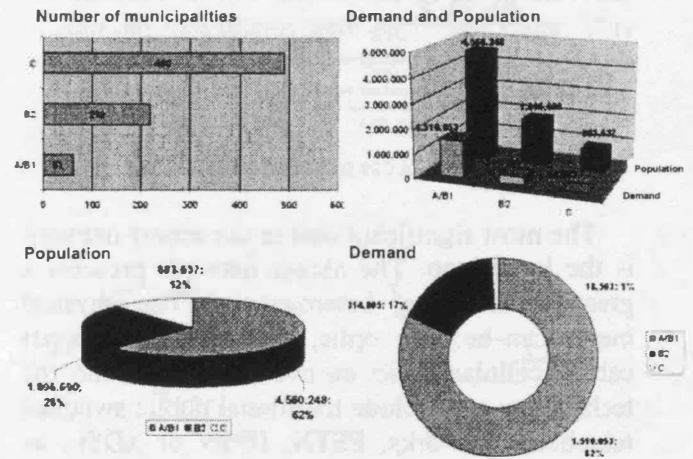

Figure 2. Main characteristics of the digital divide

3 Technological background

There are a wide range of technological alternatives to allow the deployment of high-speed telecommunication networks. The first division that we have to undertake is between the access network (urban network) and the backbone network (inter-urban network). Next figure 3 depicts the different alternatives to be considered.
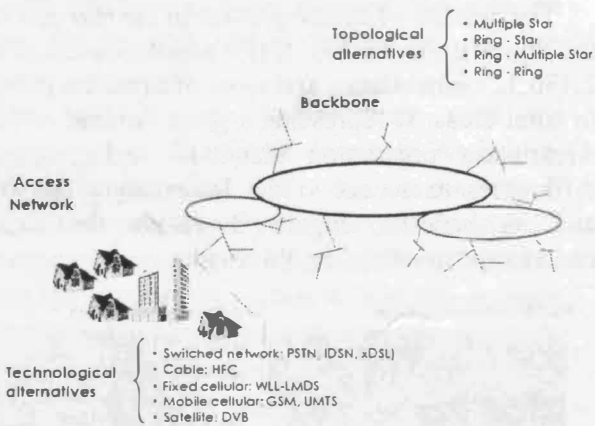
Figure 3. Access network and backbone

The most significant cost in the access network is the local loop. The access network presents a great technological heterogeneity. The physical media can be fiber optic, coaxial cables, copper cables cellular radio or even satellite. And the technology can include traditional public switched telephone networks, PSTN, IDSN or xDSL, as well as cable telecommunication networks (HFC), fixed cellular networks (WLL-LMDS) or mobile networks (GSM, UMTS) in addition to the satellite multicast (DVB). Figure 4 shows several of these alternatives.
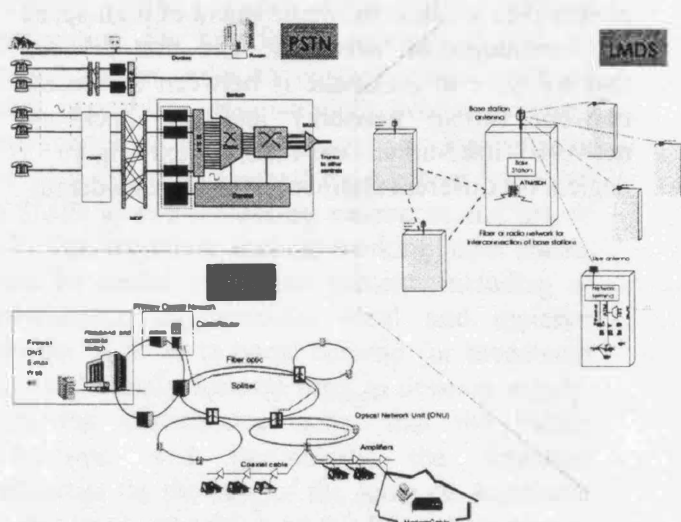

Figure 4. Technological alternatives for access networks

But the most important part of the deployment cost of a universal telecommunication networks is the cost of the backbone network. The backbone presents certain homogeneity due to the enormous advantages of the fiber optic (using SDH or WDM standards).

Several alternatives can be used for the extension of trunk links in the backbone. They depend on the transmission capacity and the length of the link:

- *Fiber optic of high quality without regenerators*. They achieve optical amplification each 100 kilometres. High quality monomode fiber is necessary, as well as erbium-doped fiber amplifiers. This system need not electro-optic conversion, and when it is combined with wavelength division multiplexer (WDM/DWDM) can reach capacities up to 100 Gb/s.

- *Fiber optic with regenerators*. This option does not require so efficient and also expensive equipment. Lower quality fiber can be used but it requires the installation of regenerators each certain distance (typically 40-50 kilometres). It is adequate for capacities up to 2.4 Gb/s and distances shorter than 150 kilometres.

- *Digital radio communication*. It is limited to capacities up to 34 Mb/s. Furthermore the land orography must be taken into account.

Next section 4 presents the design model. In it, we focus the problem in the backbone design, but considering the necessary terminal investment (the local loop). So the last mile corresponding to the selection among the technological alternatives is not considered here and it will depend on the final decision of the private company. The objective of the work is to set up an existing infrastructure capable of reaching the non-profitable points of the rural Andalusian region.

In order to conceptualise the problem we make use of Graph Theory together with bio-inspired algorithms to solve it. The process described in this paper shows the conceptualisation of a model that represents reasonably a telecommunication network, as well as the process followed in order

to achieve a cost-effective network deployment for a regional-size geographic area.

4 Model

The Theory of Graph defines a graph given by a set of nodes and arcs: $G=(N,A)$. The nodes can represent municipalities (M) or simple intersections (S) in the underlying transport network where the telecommunications network is to be placed. So, they will be active nodes (municipalities) or passive ones (typically intersections of the graph not supplying or receiving information). Arcs represent roads linking two different nodes.

We used the road network of Andalucía that allows the deployment of fiber optic cables. This initial graph was supplied by the Instituto de Cartografía de Andalucía (ICA) in Arc/Info format. The graph is shown in figure 5.
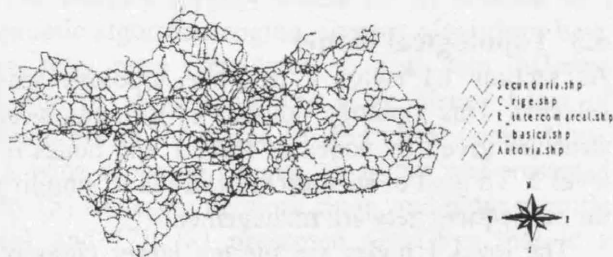

Figure 5. Initial graph

4.1 Previous hypothesis

Previously to the design of the network, the Junta de Andalucía stated some strategic decisions tha had to be taken:

1. The transmission media would be fiber optic. That allows to ensure a transmission with quality and capacity (speed in the order of hundred of Gbit/s).
2. The topology should permit the rerouting of the flows among the main municipalities in case of fails. So, the selection of a ring-tree topology was selected because it allowed this concern. The ring of such network would include all the type A municipalities. Certainly, the bi-directional self-healing ring has been the most used topology in the case of

traditional public operators due to its resilient wide coverage.

3. The ring should follow alternative fiber optic rings being currently property of operators different from the dominant operator. This is the case of the available fiber optic in the railway and electrical networks. This decision will make possible a faster deployment of the network in the less favoured areas carrying out the ring deployment in the last stage. This decision fixes the ring topology to the figure 6 case.
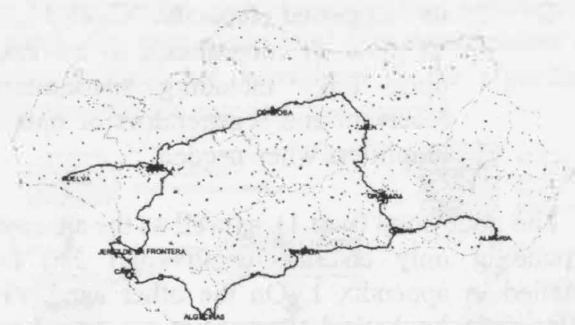

Figure 6. Resilient self-healing ring in the backbone

The ring has two special characteristics. One of them is the direct connection between Seville and Huelva. This is to avoid the Doñana Natural Park, one of the largest protected biosphere reserves in Europe. The other one is the direct connection Orgiva-Almeria. This is due to special difficulties in the road network. Both problems are solved by deploying a parallel double fiber optic cable.

4. The ring considers the data accumulation nodes for Internet connection located in Seville and Malaga.

4.2 Cost model

The infrastructure costs are classified in four categories:

1. Node costs:
    a. Fixed cost associated to the existence of the node, F_i , $\forall i \in M$. It corresponds to the terminal cable room adaptation

to connect the fibers into the DSLAM.

b. Cost depending on the capacity managed by the node. $G_i(C_i)$, $\forall i \in M$. It corresponds to the modular equipment, where the transmitters and receivers are placed.

2. Arc costs:

a. Cost depending on the arc length, $L_{ij}(D_{ij})$, $\forall (i,j) \in A$. It corresponds to the ditches and conduits.

b. Cost depending on the arc length and its supported capacity, $C_{ij}(D_{ij}, C_{max})$, $\forall (i,j) \in A$. It corresponds to the fiber optic links including transmitters, receivers and regenerators or optical amplifiers when needed.

The node costs (part 1), as well as the arc costs depending only on the length (part 2.a) are detailed in appendix 1. On the other hand, two different technological alternatives are considered to calculate the 2.b cost part.

The first option corresponds to high quality fiber optic link (without regenerators). It can be estimated as (1).

$$c_{ij}\left(D_{ij}^{sG}, C_{max}\right) = \frac{P_{SDHo}}{n_o} + \frac{P_{SDHd}}{n_d} + P_{fo}^{sG} \cdot D_{ij}^{sG} + C_{oam} \cdot \left\lceil \frac{D_{ij}^{sG}}{D_{max}} \right\rceil + 2C_{tr} \cdot \left\lceil \frac{C_{max}}{C_{10Gb}} \right\rceil \quad (1)$$

The second option corresponds to lower quality fiber optic link (with regenerators) that can be estimated as (2).

$$c_{ij}\left(D_{ij}, C_{max}\right) = \frac{P_{SDHo}}{n_o} + \frac{P_{SDHd}}{n_d} + P_{fo} \cdot D_{ij} + C_{reg} \cdot \left\lceil \frac{D_{ij}}{D_{max}} \right\rceil + 2C_{DWDM} \cdot \left\lceil \frac{C_{max}}{C_{10Gb}} \right\rceil \quad (2)$$

Where:

- P_{SDHo} and P_{SDHd} are the origin and destination SDH multiplexer costs.
- n_o and n_d are the number of links in the SDH equipment placed in node. Each SDH multiplexer can serve diverse digital links.
- D_{ij}^{sG} is the arc distance. It is covered without regenerators.
- D_{ij} is the arc distance. It can be covered with regenerators.

- P_{fo}^{sG} is the linear cost of a high quality cable of 24 monomode fibers plus the cost of connecting it.
- P_{fo} is the linear cost of a standard cable of 24 monomode fibers plus the cost of connecting it.
- C_{oam} is the cost of an optical amplification system.
- C_{reg} is the cost of a regenerator.
- D_{max} is the amplification maximum distance. Typically 140 kilometres for option 1 and 40 kilometres for option 2.
- C_{tr} is the cost of DWDM interface card (transmitter/receiver) with capacity up to 10 Gb/s.
- C_{max} is the capacity that must be equipped.

Appendix 1 details the numerical values for both options.

4.3 Topological model

As section 4.1 stated a ring-tree topology was selected. This topology consists of a hierarchical structure given by nodes of level 1 and nodes of level 2. Th goal of such architecture is to simplify the subsequent network management.

The level 1 nodes are the ten larger cities of Andalusia: Almeria, Algeciras, Cadiz, Jerez de la Frontera, Cordoba, Granada, Huelva, Jaen, Malaga and Seville plus Orgiva (a small municipality selected as part of the ring due to its strategic geographic location).

These nodes depict the ring of the backbone (figure 6). The rest of nodes are connected at one of these level 1 nodes by a tree structure. However the rest of nodes could be located into the ring structure or out of the ring. In the first case, the basic infrastructure has not to be constructed. There already exist the ditch and conduit, so we only have to consider the cost 2.b. In the other case (out of the ring) we would have to consider the costs of civil infrastructure (2.a) and transmission link (2.b). See figure 7.
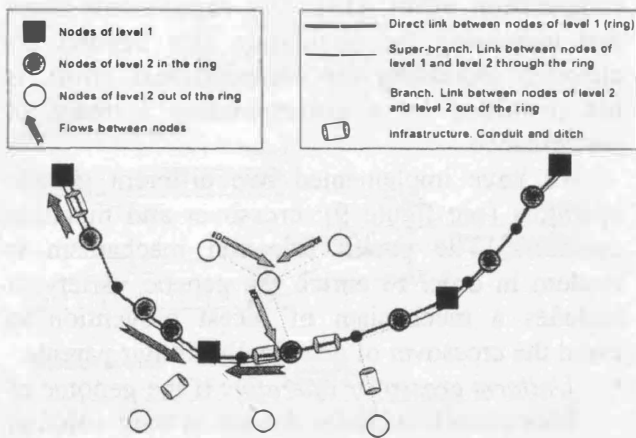
Figure 7. Topological structure

5 Decision Support System based on a genetic algorithm

The decision support system (DSS) is based on a genetic algorithm engine. Genetic algorithms have recently been considered to deal with different kinds of telecommunication problems. Most of them are in the scope of theoretical applications. A wide-scope on genetic algorithm was presented by [5] to design network rings, and more recently [6] and [7]. [8] presented GenOSys that is a topology planning tool based on a genetic algorithm to design tree network infrastructures. In this scope, [9] developed a genetic algorithm for the design of topologies in optical networks. It is case similar to [10]. Also, genetic algorithms have been used for dynamic packing, [11]. Finally, a real life implementation can be found at [12].

5.1 Decision support system structure

The DSS inputs are the cartography supplied by the ICA and the socio economic data warehouse database provided by the Institute Estadistico de Andalucia (IEA).

After processing the cartography and considering the technological model and the strategic decisions, we get the topological model, in terms of a graph. The result was a graph with

2,796 arcs and 1,920 nodes. 770 of those nodes are municipalities, the rest are simple intersections.

In the other side, the socio economic data of the municipalities of Andalusia plus the historical demand data are used to estimate the telecommunication demand for each of the municipalities. The demand values plus the financial analysis of each urban node allows us to classify the municipalities between profitable and non-profitable. This allows identifying the digital divide.

These three components (the topological model, the cost model and the classification of municipalities) are introduced in the algorithm that provides the solution. See figure 8.
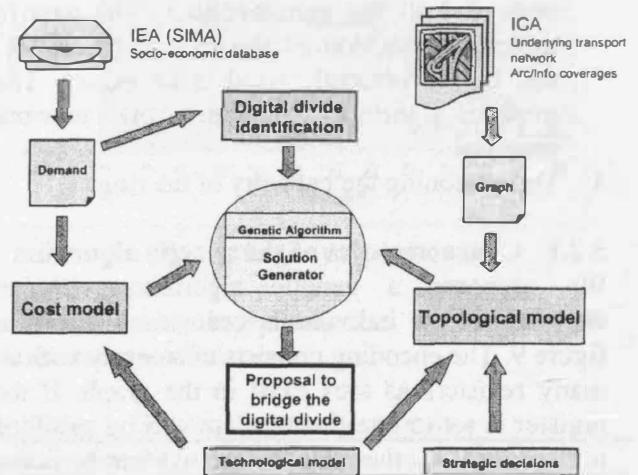

Figure 8. Decision Support System structure

5.2 The genetic algorithm

The dimensioning of the network, as well as the multiple topological alternatives to deploy such network makes the computationally complex problem. In fact, the problem can be proved as NP-Hard by simple reduction to the Steiner problem. Furthermore, given a feasible solution is easy to compute its evaluation (it can be done in polynomial time), so the problem is NP-Complete too. For this type of problems metaheuristics approaches have been proved to be suitable. And our proposal is based on a genetic algorithm.

The utilization of genetic algorithms allows obtaining good solutions in problems with a high

number of complex constraints with a difficult mathematical formulation, as this one is.

The strategy consists of generating diverse feasible solutions (with easy evaluation) and recombining them without losing feasibility. Note how each feasible solution of our problem must include the predefined ring plus the tree (super-branches and branches, see figure 7).

The procedure follows the next three steps:
1. Constructing a supra-node corresponding to the ring. The ring is conceptualised in one only node composed by all the nodes in the ring (including municipalities and passive nodes) and with so many incident arcs as each node of the ring has.
2. Constructing a tree that contains the supra-node and all the municipalities. The passive nodes (intersection of the transport network) can be conveniently used if necessary. The genetic algorithm generates the network proposal.
3. Dimensioning the capacity of the ring.

5.2.1 Characteristics of the genetic algorithm

We proposed a genetic algorithm with an encoding of the individuals genome as shown in figure 9. The encoding consists of an array with so many registers as arcs exist in the graph. If the register is set to one then the arc will be included in the solution, otherwise the arc will not be in the solution. Additionally, the genome must ensure the feasibility of the solution. So non-feasible solutions are not accepted.

After testing with different sizes, we have considered an initial population of 20 individuals. To generate them we have use the Kruskal algorithm to solve the minimum spanning tree problem –MST. Note that we are considering the ring as a supra-node. So, given 20 different sets with arc fictitious cost, we can solve the correspondent MSTs and afterwards the solutions are cleaned by erasing the passive nodes located in a terminal position.

The population size is a major factor in the effectiveness of genetic algorithms. It has been proved that relatively small populations allow reaching successful solutions with little

computation effort, [13]. Our experiments show that increasing the population size beyond 20, although increasing the computational effort, is not rewarded by a corresponding increase of performance.

We have implemented two different genetic operators (see figure 9): crossover and mutation operators. The parent selection mechanism is random in order to enrich the genetic variety. It includes a mechanism of incest prevention to avoid the crossover of genetically similar parents.

- *Uniform crossover operator.* If the genome of both parents includes the arc in their solution (i.e. it has the same register set to 1, or set to 0), then the arc is maintained in the offspring. Otherwise (only one parent has the arc) the arc is maintained with a probability equal to 0.5.

- *Mutation operator.* The operator changes a register from 1 to 0, or vice versa. That is, once one register has been randomly selected, if the arc belongs to the solution, then the arc is erased. Otherwise, if the arc does not belong to the solution, then the arc is included.

The application of the genetic operators can lead to unfeasible solutions. The possible infeasibilities are the following:

- After applying a crossover operator two trees are connected. This situation generates a new graph and cycles appear. The cycles are broken by erasing a randomly selected arc of each cycle.

- After applying a mutation operator two situations can appear:
  o If an arc is included in the solution, a cycle can appear. Then, the cycle is broken by erasing a randomly selected arc of the cycle.
  o If an arc is erased in the solution, the tree is disconnected. Then, the tree is reconnected by means of the shortest path algorithm.
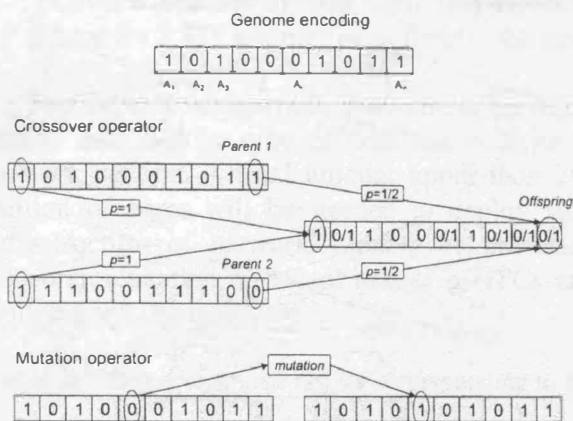
Figure 9. Genome encoding and genetic operators

Tests were carried out with different probabilities for crossover and mutation operators. Varying the crossover probability from 50% to 100% had little effect on performance, with a value of 80-90% being marginally optimal for the tests carried out. A value of 80% is used in the main runs. For mutation, values between 5% and 20% were seen to be giving better results than typically smaller values. A value of 20% is used in the main runs in order to enrich the genetic variety of the population. However, it is to be noted that the genetic algorithm is robust. That is, the test problems' solutions were achieved on the whole with a wide range of parameter values, and with no fine-tuning required to achieve efficiency.

The substitution of new individuals (offspring) by the old individuals (in previous population) is made by a ranking based replacement. We propose the use of hypergeometric functions allowing more probability of replacement for individuals with worse fitness and less probability of replacement for individuals with better fitness. So, the individual in ranking position-i, have a replacement probability equal to $q \cdot (1-q)^i$, where q is the replacement probability of the worst individual. The value for the parameter q is progressive. It starts with a low value of q in order to explore the feasibility region and then the value is progressively increased to exploit the niche quality.

Additionally, we incorporated an individual duplicity control in the population generation.

The number of generations of the genetic algorithm can be a critical parameter when we try to reach efficiency of the solution and short time execution. Genetic algorithms are iterative, and, therefore, they can take very much time of execution. However the advantage of genetic algorithms is that they can be stopped at any time having the better solution at the moment. After several tests, we selected a number of 50 iterations. The learning curve of the algorithm is depicted in figure 10.
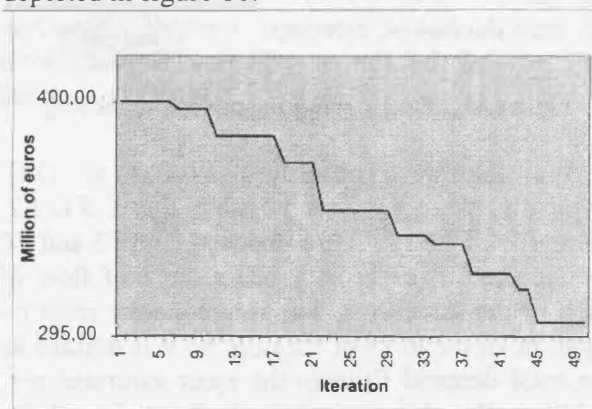

Figure 10. Learning curve

Next Table 1 summarizes the value of parameters selected.

Table 1. Genetic algorithm parameters

Population size, N	20
Crossover operator probability (mutation operator)	0,8 (0,2)
Ranking based replacement probability, q	0,2/0,4/0,6/0,8[a]
Maximum number of generations	50

[a] Progressive increase of q each ten generations.

The algorithm pseudocode is described in the appendix 2.

5.2.2 Final dimensioning of the ring capacity

We proposed a bi-directional self-healing ring. This allows rerouting the demand flows in case of fail. The problem is to determine the capacity of the ring that allows rerouting all the flows in case of fail. As the ring capacity is directly related to the ring cost, we minimize the capacity capable of guaranteeing the demand flows.
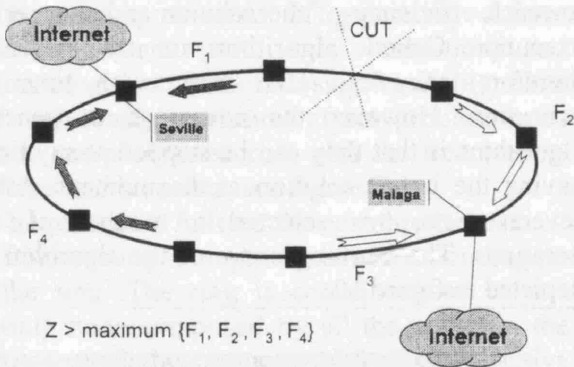
The generic case is depicted in figure 11.

Figure 11. Generic rerouting process in the ring

We follow a procedure similar to [14]. Typically, there are four possible flows: F1, F2, F3 and F4. F1 and F2 are imposed, and F3 and F4 are selected in order to process the half flow in each of the directions. The ring capacity must be equal in all the links of the ring. So it is defined as the total demand flow in the most saturated arc. Additionally, this must be calculated for all the possible cuts in the network.

6 Network solutions

This section shows the results reached for the case study. It includes the topological solutions, as well as the investment required. Finally, a sensitive analysis is evaluated.

6.1 Results with basic costs

The compilation of the input data together with the decision support system supplied us a cost effective solution whose topological architecture can be observed in figure 12. The figure shows three stages for the deployment that we have named as S1, S2 and S3. They correspond to 80%, 90% and 100% of population coverage respectively. We used the costs described in appendix 1.
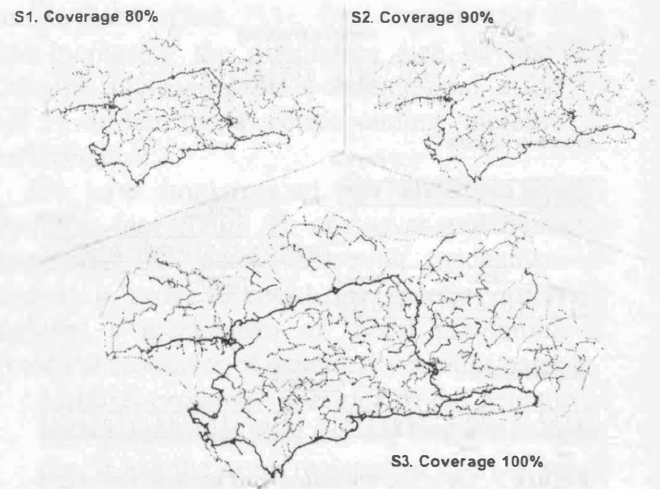

Figure 12. Graphical solution: Deployment by stages (80%, 90% and 100%)

Solution S1 includes 616 municipalities. Solution S2 deploys the network over 700 municipalities and finally solution S3 covers the entire 770 municipalities.

Figure 13 shows a zoom over the Huelva zone allowing us to reach a more precise interpretation of the topological results that were obtained and managed by the GIS system.
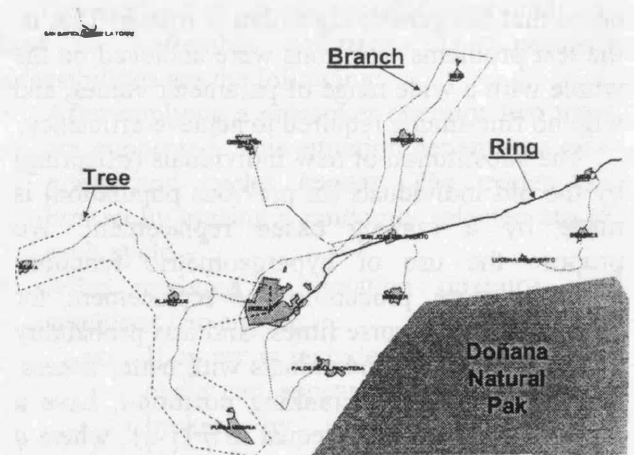

Figure 13. Zoom over Huelva zone

The data for solution S3 corresponds to the following values:

- 7,101 kilometres of ditches and conduits (civil engineering). The ring has 1,158 kilometres.

- 14,698 kilometres of fiber optic (digital link). There are 3,953 kilometres of fiber in the ring.

The Table 2 summarizes the main economical results detached by type of cost and by type of network section. A total amount upper than 295 million of euros will be needed to deploy such infrastructure of network capable of providing telecommunication universal access of ITCs and bridging the digital divide.

Table 2. Main economical results corresponding to S3

Costs	Civil engineering	Digital link	Node location	Total
Ring	22,935,553 €	41,353,871 €	1,045,000 €	65,334,424 €
Rest	117,671,808 €	84,723,572 €	27,466,000 €	229,861,380 €
Total	140,607,361 €	126,077,443 €	28,511,000 €	295,195,804 €
%	47.63%	42.71%	9.66%	100.00%

6.2 Sensitivity analysis

In order to analyse possible modifications to the estimated data, we studied the effect of diverse variations in the cost function.

### 6.2.1 Fiber optic substitution by digital radio link

Firstly, we studied the possible substitution of fiber optic by digital radio links. This alternative is only suitable for those municipalities located at the end of the trees and with a capacity under 60 equivalent ADSL lines (256 kb/s) corresponding to an E4 link. Additionally a distance not larger than 10 kilometres is recommended for radio link deployment.

There are 275 municipalities in a terminal position of the tree. Only 155 of them are not farther than 10 kilometres.

The radio communication needs the placement of two antennas directly faced. In other case a third antenna will be needed to allow the communication. We have considered a typical facing direct section of 5 kilometres, so there are 74 municipalities requiring a connection by two antennas and 81 requiring a connection by three antennas.

So the required investment in digital radio link is valuable as 13,342,000 €. This investment would substitute diverse sections of fiber optic network. However the reduction in civil engineering is lower due to the possible sharing of the conduit by diverse links. This configuration is illustrated in figure 14. If municipality A is served by radio, it must be provided from C, but only the section investment between s and A can be avoided. The part C-s is needed for the link between C and B.
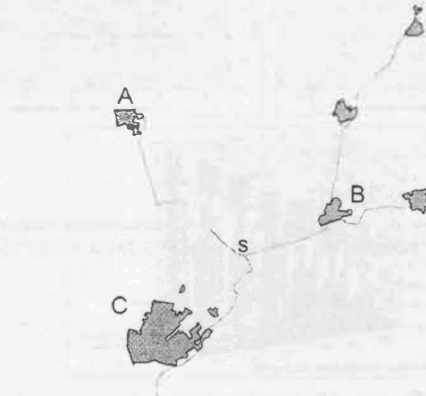
Figure 14. Example of substitution of fiber by radio link

Therefore, the saving corresponds to 777 kilometres of fiber and 762 kilometres of conduit. The Table 3 summarizes the results.

Table 3. Fiber optic network saving

Civil engineering[1]	Link Cost[2]	Node cost[3]	Total
15,093,302 €	5,441,289 €	77,500 €	20,612,091 €

[1] Arc cost depending on the distance. Civil engineering.
[2] Link costs depending on the distance and capacity. Digital link.
[3] Node costs depending on the capacity managed by the node.

So the network cost savings is estimated in 7,270,091€. It represents a reduction of 2,5% with respect to the scenario S3.

6.2.2 Variation in the cost function

Another possibility that was analysed is the modification of the cost function values. In order to do so, we have studied the sensitivity respect to the civil engineering cost and the possible scale economies that could be achieved in function of the volume of acquisition of fibers.

In figure 15, we represent the variation of the cost with respect to the civil engineering cost, with respect to the discount per volume of acquisition and also the combined effect.
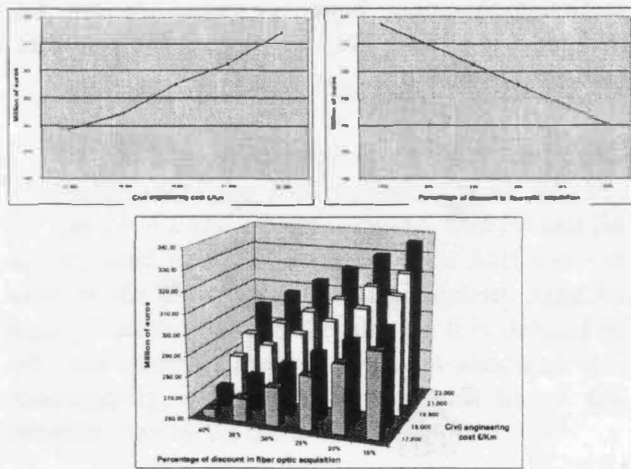

Figure 15. Cost sensitivity

The civil engineering costs are mainly located in the trees (78%) as the Table 2 indicates. For these cases, the civil engineering costs achieve 51% of the total. The figure reveals a possible variation around 13%.

The solution was calculated supposing a fiber optic cost discount of 30% corresponding to habitual discounts in massive acquisition. Having this data, the fiber costs are assessed as the 82% of the link costs, representing the 43% with respect to the overall. This kind of discount is difficult to set and depends on the contract commercial transaction. The figure reveals a possible variation around 11%.

Finally the last figure depicts the combined variation of costs with respect to the civil engineering costs and the possible discounts. In this case, the maximum variation is equal to 25%.

6 Conclusions

The private companies are not responsible of the digital divide experimented between diverse parts of the society. They cannot provide new high-speed telecommunication network infrastructures as far as not profitable points of the rural areas. For these aspects the governments (especially the local and regional governments) have to assume their responsibilities to avoid the digital divide between the rural and urban zones, as the European Commission and the United Nations have often highlighted. In order to do so, this kind of real practice studies are specially indicated. It must be promoted the proposals of cost-effective networks allowing the incorporation of the rural zones into the Information Society.

We have proposed a decision support system based on a genetic algorithm decision engine to construct alternative fiber optic networks allowing the progressive inclusion of the rural areas of Andalucía in the Information Society. The system was revealed as an adequate instrument to do so, and the proposal is carrying out to practice by the Andalusian Government.

Acknowledgments

Appendix 1. Costs

The values that we have used in the cost model are shown in Table 4 and Table 5.

Table 4. Fiber optic costs.

	Concept	Cost
F_i	Terminal room adequation cost	30,000 €
$G_i(C_i)$	Low quality modular equipment cost	3,000 €
	Medium quality modular equipment cost	3,000 €
	Modular equipment WDM	60,000 €
$L_{ij}(D_{ij})$	Civil engineering costs (ditch and conduit)	19,800 €/Km
$C_{ij}(D_{ij}, C_{max})$	2nd window fiber optic cable cost [a]	7,000 €/Km
	3rd window fiber optic cable cost [a]	7,000 €/Km
	3rd window fiber optic cable cost. It includes displaced dispersion fiber for long distances vain without electro-optic regenerators [a]	25,000 €/Km
	Transmitter/receiver E1 cost	200 €
	Transmitter/receiver E4 cost	500 €
	Transmitter/receiver STM1 cost	1,500 €
	Transmitter/receiver STM4 cost	6,000 €
	Transmitter/receiver STM16 cost	15,000 €
	Transmitter/receiver STM64 cost	360,000 €
	Regenerator cost (each 40 Km)	3,000 €
	EDFA cost	90,000 €

[a] It has been considered a discount equivalent to 30% for the fiber optic cost corresponding to habitual discounts in massive acquisition.

Table 5. Digital radio link costs.

Concept	Cost
Antenna, mast and electronic required	30,000 €
Chassis of nodes (in extreme of sections)	5,000 €
Transmitter/receiver	200 €

Appendix 2. Genetic algorithm pseudocode

```
Generate the population
Calculate the fitness population
WHILE Generations < 50
Ordinate the fitness population and
estimate the probability of
replacement
Random selection of p
  IF p < 0.8 THEN 'Crossover operator'
      Randomly selection of parents
      Parents' incest prevention
      IF No incest THEN
            Crossover -> offspring
  END IF
  ELSE      'Mutation operator'
      Randomly selection of parent
      Mutation -> offspring
  END ELSE
  Individuals duplicity control
    IF No duplicity THEN
        Evaluation of the individual
        fitness
        Selection of individual for
        replacement (q)
        Population update
        Modification of the population
        fitness table and probability of
        replacement
        Increase Generations
    END IF
END WHILE
Solution = Best fitness individual
```

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