

Reliable Critical Infrastructure: Multiple Failures for Multicast using Multi-Objective Approach

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Abstract:

Multicast is the keystone for multimedia Internet. Multicast is one of the new and most used services in telecommunication networks. However, these networks meet big challenges when facing failures from diverse factors, including natural disasters and bad configurations. Networks operators need to establish mechanisms to maintain available multicast services, and plan actions to handle incidents. We study and implement an elitist evolutionary algorithm based on Strength Pareto Evolutionary Algorithm - SPEA. Our implementation recalculates network routes, even when there are multiple failures. The results indicate that our product finds lower-cost and higher-availability multicast tree to protect multicast services.

Keywords: resilience, protection, survivability networks, multi-objective evolutionary algorithm.

1 Introduction

Multicast is one of the new and most used services in telecommunication networks. Some applications on the Internet use a multicast service which is a key factor in multimedia, video conferencing, distributed games, Internet television, and telepresence. A multicast service simultaneously sends messages from only one source to a group of destinations creating a multicast tree over a network. Networks are exposed to several sources of failure, including misconfiguration or operational errors, natural disasters, attacks, and environmental challenges. Additionally, to maintain the services, they must consider unusual but legitimate traffic [1], such as peak traffic on specific hours or dates. Due to multicast applications demand important amount of traffic, they need a mechanism to protect them from network failures. The Internet, for example, has been designed to survive random failures. If a node is down, the reliable protocol is able to reroute the traffic around and use alternative connections.

In networking, Resilience and Survivability refer to the abilities of the network to overcome failures and maintain its services working. The study of resilience and survivability has become an important aspect of managing infrastructure in multicast networking. In this paper, we formulate a mechanism to protect a multicast service when the network experiences multiple failures. Failures in multicast have been widely studied [2] [3]. A common strategy to face this problem is finding a *redundant multicast tree* (RMT). Some authors consider that a RMT could be completely link-disjoint from the original. They propose to find a RMT with the minimal cost. To determine the optimal RMT, we consider the NP-hard *Steiner tree problem* [4]. Several algorithms have been proposed to deal with this issue, such as Topological methods [5], or the *Nearest Participant First* (NPF) [6]. Furthermore, there are network protocols which calculate a multicast tree with the minimal cost, such as MOSPF, PIM-DM, PIM-SM, and CBT.

However, there are some limitations with existing approaches. First, the algorithms that calculate RMTs were designed to optimize only one decision variable; thus, they use only distance to find the minimum cost tree. Furthermore, algorithms and protocols previously mentioned were tested with single failures, it means, when only a link disruption occurs. Nonetheless,

telecommunication operators need to find not only routes with the minimal cost, but also routes with high availability. Moreover, operators require techniques to plan and reconfigure the network where a set of links are damaged or eliminated.

We propose a mechanism to protect multicast services, with the maximum availability and the minimum cost, considering multiple failures and diverse decision variables. Our approach applies an heuristic multi-objective evolutionary algorithm (MOEA) which is a stochastic search method to estimate the optimal RMT. We implement the Strength Pareto Evolutionary Algorithm (SPEA) which is an elitist evolutionary algorithm that finds Pareto-optimal solutions [9]. The used method has polynomial computational complexity $\mathcal{O}(mn^2)$ where m is the number of arcs and n nodes [10]. Result exhibits possible configurations after multiple failure for this problem considered NP-hard.

2 Multicast Protection Problem

Multicast Protection Problem (MPP) is analysed from the communication survivability and resilience view. Multicast services, methods for provisioning, and failures are presented by formal description. A network is depicted as a weighted, directed, connected graph $\mathbf{G} = (\mathbf{N}, \mathbf{A})$. A set \mathbf{N} of n nodes and a set \mathbf{A} of arcs. Nodes are elements labelled $1 \dots n$ and an arc is an ordered pair of nodes, an arc between nodes i and j is denoted by $(i, j) = \{(i, j) | i, j \in \mathbf{N}\}$. A network is represented by an $n \times n$ adjacency matrix \mathbf{A} . The ij th element is 1 if $(i, j) \in \mathbf{A}$ and 0 otherwise.

Arc symbolizes a communication link in the network; so, it has assigned two link's attributes: cost and availability. Cost indicates the length of the link and availability is the probability that the link works during a period of time. These attributes are represented by $n \times n$ matrices $\mathbb{W} = \{w_{ij}\}$ for distance and $\mathbb{V} = \{v_{ij}\}$ for availability. Table 1 contains used notation to model the problem.

\mathbf{N}	Set of nodes labelled $\{1, 2, \dots, n\}$	s	Multicast source node $s \in \mathbf{N}$
\mathbf{A}	Set of arcs $\{(i, j) i, j \in \mathbf{N}\}$	D	Destinations set $\{d_1, d_2, \dots, d_l : d_i \in \mathbf{N}\}$
\mathbf{A}	Adjacency matrix, $n \times n$	T	Multicast Session $T = (s, D)$
\mathbb{W}	Matrix of cost, $\mathcal{W}(\mathbf{A}_{ij}) = w_{(i,j)}$	\mathbf{T}	Multicast session subgraph $\mathbf{T} = (\mathbf{N}, \mathbf{A}') \mathbf{A}' \subseteq \mathbf{A}$
\mathbb{V}	Matrix of availability, $\mathcal{V}(\mathbf{A}_{ij}) = v_{(i,j)}$	\mathbf{F}	Set of failures $\{f_1, f_2, \dots, f_k f_i \in \mathbf{A}\}$

Table 1: Graph notation

Definition 1. Multicast session is delivery data from source node s to l destinations nodes that belong to set D .

According to definition 1, we model a multicast session as a graph \mathbf{T} . It is a directed tree with root s and terminal vertices $d_i \in D$. \mathbf{T} is a set of paths from s and $d_i \in D$. A path P is a walk without repeated nodes, and it is represented as a nodes sequence $p_j = \{s, i_1, i_2, \dots, d_j\} : s, i_k, d_j \in \mathbf{N}$.

A failure is a link disruption; therefore, multiple failures are described as a set of damaged or eliminated links. This set, called *vector of failures*, is labelled by \mathbf{F} where k is the number of edges that have failed. The failures are uncorrelated, and they occur following a uniform random distribution.

Definition 2. A failure f_i is a pair $(i, j) \in \mathbf{A}$, where $i, j \in \mathbf{N}$. After a failure the graph G changes to $\mathbf{G}' = (\mathbf{N}', \mathbf{A}'), \mathbf{N}' \subseteq \mathbf{N}$ and $\mathbf{A}' \subseteq \mathbf{A}$

Then, the multicast protection problem against multiple correlated failures is described as follows.

Definition 3. Given a weighted graph $\mathbf{G} = (\mathbf{N}, \mathbf{A})$, a multicast demand T , and a set of links that have failed \mathbf{F} , the Multicast Protection Problem (MPP) is providing a RMT \mathbf{G}' with maximum availability $\mathcal{V}(\mathbf{G}')$ and minimum cost $\mathcal{W}(\mathbf{G}')$.

MPP is similar to find the optimal tree, which is a classic graph theory problem knowing as *Steiner tree problem* that was proven as NP-hard. Consequently, MPP is also a NP-hard problem.

3 Optimization Model

In order to make feasible the computation, the network is represented by a matrix of adjacency \mathbf{A} . We assume that all links on the network are directional. The matrix of adjacency has zero entries on the main diagonal because there are not loops in the vertices. The attribute values of cost and availability are represented into matrices \mathbb{W} and \mathbf{V} .

$\mathcal{W}(\mathbf{G})$ is the cost function of graph \mathbf{G} which is the sum cost of all arcs in \mathbf{G} (1). Similarly, availability function $\mathcal{V}(\mathbf{G})$ is the conditional probability that all arcs in \mathbf{G} are able (2).

$$\mathcal{W} : G \rightarrow \mathfrak{R}, \quad \mathcal{W}(G) = \sum_{(i,j)} w_{(i,j)} \quad \forall i, j \in G \quad (1)$$

$$\mathcal{V} : G \rightarrow [0, 1], \quad \mathcal{V}(G) = \prod_{(i,j)} v_{(i,j)} \quad \forall i, j \in G \quad (2)$$

Figure 1 shows three trees able to carry data to multiple destinations. Figure (1a) is a graph representing a complete network; Figure (1b) is a subgraph able to reach both destinations; Figure (1c) is another subgraph reaching the same destinations. Note that both subgraphs are multicast trees, but these are disjoint trees; it means, one is a multicast protection tree of the other.

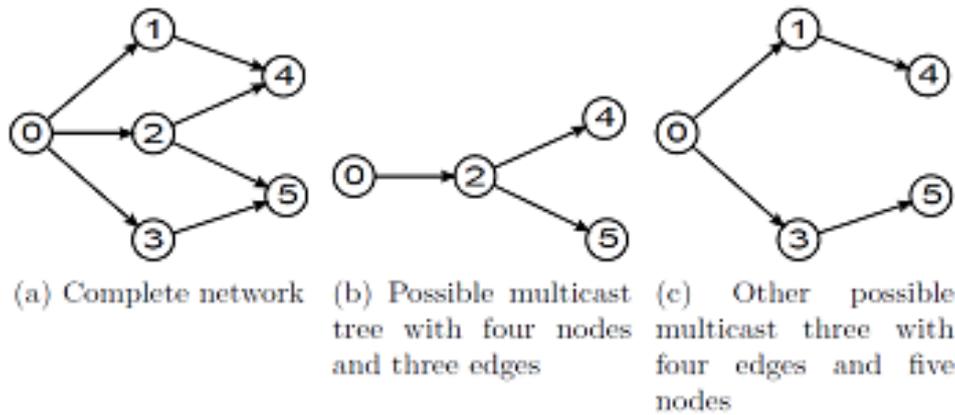


Figure 1: Network and Multicast Protection Tree for a demand from node 0 to nodes 4 and 5.

3.1 Variable definition

We set $x_{i,j}$ in (3) as a binary decision variable that symbols if an edge is used or not by the session T . $x_{i,j}$ corresponds to the input (i, j) value in the matrix of adjacency \mathbf{A} .

$$x_{(i,j)} = \begin{cases} 1 & \text{when the link is used from node } i \text{ to node } j, \\ 0 & \text{in other case.} \end{cases} \quad (3)$$

3.2 Objective functions and constraints

The expressions (4) and (5) are the objective functions. Recall that the goal is to find a set of optimal trees that minimize the total cost and maximize the total availability.

$$\min \mathcal{W}(G) = \min \sum_{(i,j)} x_{(i,j)} w_{(i,j)} \quad \forall i, j \in A \quad (4)$$

$$\max \mathcal{V}(G) = \max \prod_{(i,j)} x_{(i,j)} v_{(i,j)} \quad \forall i, j \in A \quad (5)$$

In networking, a multicast session is a particular case where only one package is sent from s and multiples copies are delivered to d_i . Multicast session is a variation of the transport problem. In the transport problem an intermediate node i_k receives and delivers same amount of goods. In multicast, an intermediate node can *replicate* packages and send them by several output arcs. Then, the multi-objective optimization problem is subject to:

$$x_{(s,j)} = 1 \quad j \in A \quad (6)$$

$$x_{(j,d_i)} = -1 \quad j \in A \quad (7)$$

$$x_{(i,j)} \leq \sum_k x_{j,k} |x_{(i,j)} = 1, k \in A \quad j \neq s, j \neq d_i \quad (8)$$

$$x_{(i,j)} \geq 0 \quad i, j \in A \quad (9)$$

Constraints (6) and (7), called constraints of offer and demand, are associated to root and destinations nodes. Constraint (8) guarantees the replication of package, and the last constraint is a positive flow.

4 Case Study

In this paper we study multiple failures in telecommunications networks and reliability for multicast services. We propose a different mechanism to reconfigure the network. As an example, we propose a case study, generate multiple failures, run our implementation to avoid failed links and generate a new RMT. This work is divided into three stages. First, we implement a mechanism based on SPEA. Secondly, COST239 PAN-EUROPEAN Network tests the implementation. Finally, the simulation is executed, and data is obtained to be analysed.

4.1 Creating an evolutionary algorithm

Genetic algorithm (GA) is a stochastic search method based on chromosomes. Each chromosome represents a valid solution to the problem. Space of solution Ω contains all feasible solutions that satisfy problem constraints. Thus, particular solution $\omega_i \in \Omega$ is a tree represented by a chromosome. GA initiates a population P which is a set of chromosomes randomly generated. After, each chromosome is rated by the objective function or *fitness function*. Then, a pair of solutions, or individuals, are selected and produce an offspring by mixing their genetic information. Successor solutions are generated by combining two parent states or modifying a single

one, analogue to natural selection. There are two kind of evolutionary algorithms, non-elitist and elitist ones. Non-elitist algorithms use whole latter population for the next iteration; also, this procedure allows exploit non-dominated solutions, it means, found optimal Pareto \mathcal{P} solutions. Second, elitist algorithm gives the chance to preserve the best solutions, or *elite solutions* \bar{P} , directly to next generation. This kind of problem representation is used to solve complex optimization problems [11]. We use a GE optimization in this paper to solve RMT problem.

Strength Pareto Evolutionary Algorithm - SPEA

Zitzler and Thiele proposed an evolutionary algorithm called SPEA [9]. This algorithm maintains elitism by an external population \bar{P} . This population is a collection of non-dominated solutions $\bar{\omega}$. Let say $\bar{\omega}$ dominates ω , $\bar{\omega} \succeq \omega$, if $\mathcal{W}(\bar{\omega}) \leq \mathcal{W}(\omega)$ and $\mathcal{V}(\bar{\omega}) \geq \mathcal{V}(\omega)$. The algorithm finds non-dominated solutions and compares them with previous external population until segregate a new external population. This algorithm preserves elitist population \bar{P} . SPEA has been widely used to solve network optimization problems [11]. This particular problem was faced from two phases. First, we used a high-level modelling system for mathematical optimization which allows to solve linear, nonlinear, and mixed-integer optimization problems. Second, a SPEA genetic algorithm was implemented. This method demonstrated polynomial computational complexity $\mathcal{O}(mn^2)$ where m is the number of arcs and n nodes [10] solving a problem considered NP-hard [12].

Chromosome

The chromosome is a tree that can be represented by an adjacency matrix subset of \mathbf{A} . However, a matrix representation has difficulties when it is necessary to reconstruct a unique route. Consequently, we change the chromosome representation for a *list* of paths following the original model. The Figure 2 depicts the structure representation of a chromosome.

Path p_0	s	...	d_0
Path p_1	s	...	d_1
⋮			
Path $p_{(k-1)}$	s		$d_{(k-1)}$
Path p_k	s		d_k

Figure 2: Chromosome as a list of paths.

4.2 SPEA implementation

We design and implement a specific tool to find optimal RMTs. Initial population P_0 is generated by a random tree generator, Algorithm 1. Random tree generator creates random walks from s node to each destination node d_i . Also, we implement matrix operations and processes for creating multicast demands T , operators for chromosomes, including crossover and mutation. Algorithm 2 is a generalized description that we follow to generate a set of solutions.

```

input : actual, d, path, visited
output: Random path p
adjacents  $\leftarrow$  actual.getAdjacents();
if adjacents. contains(d) then
  | path.add(actual);
  | return path;
end
for  $i \leftarrow 1$  to adjacents.length() do
  | new  $\leftarrow$  RandomChoose(adjacents);
  | visited.add(new) ;
  | RandomPath(new, d, path, visited)
end

```

Algorithm 1: Random path generator

```

input :  $E, n, k, numGenerations$ 
create initial population;
for  $i \leftarrow 1$  to numGenerations do
  |  $\overline{P}_i \leftarrow$  find non-dominated ( $P_i$ );
  | if  $\overline{P}_i > \overline{N}$  then
  | | clustering( $\overline{P}_i$ );
  | end
  |  $\overline{P}_{i+1} \leftarrow \overline{P}_i$ ;
  | calculate Fitness ( $\overline{P}_{i+1}$ );
  | calculate Strength ( $\overline{P}_{i+1}$ );
  | selection by roulette ( $\overline{P}_{i+1}$ );
  | crossover;
  | mutation;
  |  $P_{i+1} \leftarrow$  create new population;
end

```

Algorithm 2: SPEA algorithm

Simulation scenario

COST239 PAN-EUROPEAN network tests the implementation. The network with 28 nodes represents the Internet backbone, and connects main cities in Europe. After setting topologies, we set the parameters, and generate random link failures in the tree of multicast service. Table 2 summarizes simulation parameters. Then, our implementation compute RMTs and they are stored for analysis.

Parameter	Value
Number of generations	15
Initial population size	10
Max population size	30
Max non-dominant population	20
Crossover probability	0.2
Mutation probability	0.2

Table 2: Simulation Parameters

5 Analysis and Conclusions

After running our implementation, we notice that SPEA, for reliability in MPP and network design, is a powerful tool. Figure (3) is an example using COST239 PAN-EUROPEAN Network as test topology. First, the implementation find a tree, which in our hypothesis is the original multicast tree (3a). After that, the multiple failures module chooses arcs and delete them, simulating link failures and a reaction against the service. Then, our implementation of SPEA for reliable networks identifies those paths that become unreachable and creates new protection routes. Figures (3b) and (3c) show two examples of RMTs calculated to reliable network infrastructure.

However, COST239 and NSFNet are small network topologies to test real performance of the implementation. For that reason, we also test it with a generated topology. We create a virtual

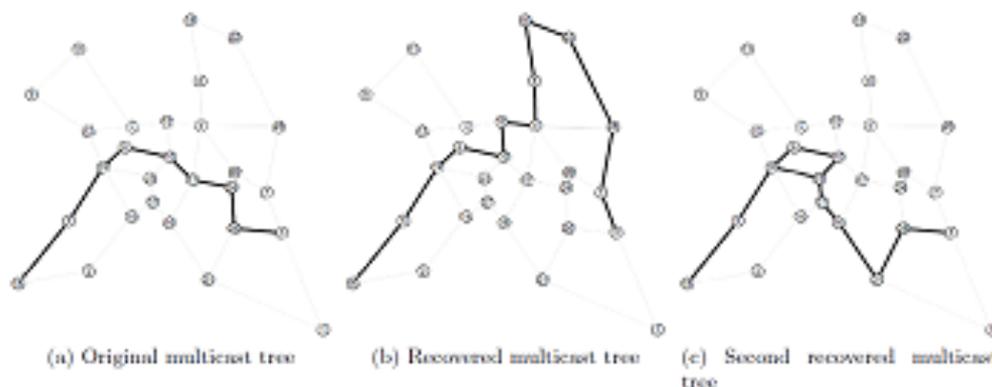


Figure 3: Multicast network trees

over all network including thirty nodes and twenty-nine arcs for each one. Results are condensed in Figure (4). We can observe that the network is able, high availability and low cost. When it experiments failures, our algorithm recalculate the multicast tree and re-configure the paths. In some cases, the services can be fulfilled without problems; however, services can be degraded or cancel in the worst case. As a result, we can establish a correlation between the topologies, mechanisms to find RMTs, and complexity needed to solve alternatives trees. Here we can notice that our implementation finds new low-cost high-availability trees, even if the failures increase.

We present and investigate a different approach of protection of survivable multicast sessions in networks. Results allow to optimize designs in both variables: total cost and availability. We also deploy a SPEA heuristic algorithm to MPP. We use SPEA due to its reduced computational time and complexity $\mathcal{O}(mn^2)$. After using our approach in the PAN-EUROPEAN and the NSFNET networks, we find that the performance of the multicast protection schemes is better when the size of the network is bigger and the network experiences uncorrelated multiple failures. Moreover, the results show that our implementation is an important tool to support decisions for a network operator with similar conditions to this scenario. Also, results display the trade-off between cost and availability in a network and present how multicast sessions can be restored or re-configured using this tool.

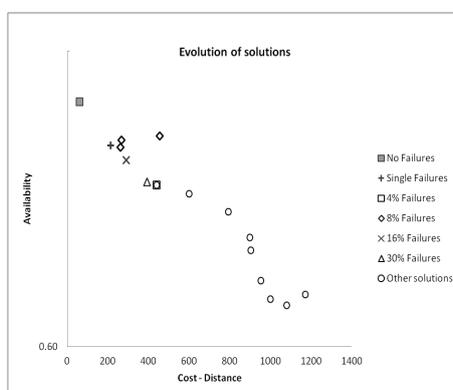


Figure 4: Cost and availability for solutions RMTs

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