Applied Soft Computing 36 (2015) 578–588

Contents lists available at ScienceDirect

Applied Soft Computing

journal homepage: www.elsevier.com/locate/asoc

System reliability maximization for a computer network by finding the optimal two-class allocation subject to budget

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ARTICLE INFO

Article history:
Received 11 April 2011
Received in revised form 28 April 2014
Accepted 29 July 2015
Available online 5 August 2015

Keywords:
Optimal two-class allocation
System reliability
Capacitated-flow network
Genetic algorithm
State-space decomposition
Allocation cost

ABSTRACT

In the real world, a computer/communication system is usually modeled as a capacitated-flow network since each transmission line (resp. facility) denoted by an edge (resp. node) has multiple capacities. System reliability is thus defined to be a probability that *d* units of data are transmitted successfully from a source node to a sink node. From the perspective of quality management, system reliability is a critical performance indicator of the computer network. This paper focuses on maximizing system reliability for the computer network by finding the optimal two-class allocation subject to a budget, in which the two-class allocation is to allocate exactly one transmission line (resp. facility) to each edge (resp. node). In addition, allocating transmission lines and facilities to the computer network involves an allocation cost where the cost for allocating a transmission line depends on its length. For solving the addressed problem, a genetic algorithm based method is proposed, in which system reliability is evaluated in terms of minimal paths and state-space decomposition. Several experimental results demonstrate that the proposed algorithm can be executed in a reasonable time and has better computational efficiency than several popular soft computing algorithms.

1. Introduction

With the internet popularization in our modern life, data and information are usually transmitted through computer/communication systems. Since the quality of data transmission deeply influences on the effect of organizational operation, many organizations focus on the issues of system reliability evaluation and improvement to increase the transmission quality, especially for the issue of system reliability maximization. A computer system is usually modeled as a network composed of edges and nodes, in which each edge denotes a transmission line and each node denotes a facility. Generally, a transmission line is combined with several physical lines such as fiber cables, coaxial cables or twisted pairs and a facility is combined with several devices such as routers, hubs, switches or bridges. Because each physical line (resp. device) has a capacity and may fail due to failure, maintenance, etc., each transmission line (resp. facility) has multiple states. That is, the computer network is multistate, and thus is a typical capacitated-flow network [1–8]. System reliability is thus defined to be a probability that *d* units of data are transmitted successfully from a source node to a sink node, and is one critical performance indicator of the computer network. Several studies evaluated system reliability in terms of minimal paths (MPs) [1,2,4] or minimal cuts (MCs) [1–3] without node failure. An MP is a set of edges and nodes whose proper subsets are no longer paths. Lin evaluated system reliability with node failure in terms of MPs [5], and then in terms of MCs [6].

From the perspective of quality management, system reliability maximization is a practical topic to discuss. Several studies [9–11] related to system reliability maximization determined the optimal network topology for a binary-state computer network. For multistate computer networks, Levitin and Lisnianski [12] proposed a technique integrating a universal generating function and genetic algorithm (GA) to solve a family of system reliability maximization problems, such as structure optimization, optimal expansion, and maintenance optimization. Ramirez-Marquez and Rocco [13] introduced an evolutionary optimization approach to solve the stochastic network interdiction problem. The problem considers the minimization of the transmission cost associated with an interdiction strategy such that the maximum flow can be transmitted between a source node and a sink node under a given reliability requirement. Considering that the resources are allocated to protect the edges under an evenly distributed attack strategy,

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http://dx.doi.org/10.1016/j.asoc.2015.07.037
1568-4946/

Ramirez-Marquez et al. [14] presented a network optimization model to maximize the survivability of the network for successfully transmitting a specific flow from a source node to a sink node.

In addition to these issues, there exists a problem to search for the optimal component allocation with maximal system reliability for the computer network with a given network topology. In this problem, all components are separated to be two sets which are a set of Class 1 components (transmission lines) and the other set of Class 2 components (facilities). In particular, allocating a Class 1 (resp. Class 2) component to an edge (resp. node) involves the allocation cost, in which the cost for allocating a Class 1 component depends on its length. Therefore, this paper devotes to the System Reliability based Two-Class Allocation problem subject to a Budget. For the convenience, such a problem is named SR2CAB problem herein. In this problem, the two-class allocation means that each Class 1 (resp. Class 2) component can be allocated to at most one edge (resp. node) and each edge (resp. node) must include exactly one Class 1 (resp. Class 2) component. With multistate Class 1 and Class 2 components, any computer network under a two-class allocation is regarded as a capacitated-flow network.

Intuitively, an implicit enumeration method which enumerates all possible allocations may be applied to solve the SR2CAB problem. However, it is time-consuming for larger networks. Instead, we develop an efficient algorithm based on GA, namely SR2CAB-GA, to solve the addressed problem. The reason is that GA is a robust search technology and recently has been validated to be suitable for the allocation problems [15,16], such as Lin and Yeh [7,8], Lee et al. [17], Salcedo-Sanz et al. [18], Salcedo-Sanz and Yao [19], Kaminer and Ben-Asher [20]. In the proposed algorithm, a two-class allocation is represented as a chromosome (a solution), and system reliability is evaluated in terms of MPs and state-space decomposition. Through this algorithm, the optimal two-class allocation with maximal system reliability can be found in a reasonable time.

The rest of this paper is organized as follows. The assumptions are shown in Section 2. The problem formulation is discussed in Section 3. Section 4 subsequently develops the SR2CAB-GA to solve the SR2CAB problem. Two numerical examples are adopted to demonstrate the computational efficiency of the proposed algorithm while comparing with several soft computing algorithms. Conclusions are described in Section 6, along with recommendations for future research.

2. Assumptions

Let (**E**, **N**) be a computer network with a source s and a sink t where $\mathbf{E}=\{e_i|1\le i\le n\}$ denotes the set of n edges connecting a pair of nodes and $\mathbf{N}=\{e_i|n+1\le i\le n+q\}$ denotes the set of q nodes except for s and t. Let $\mathbf{L}=\{L_i|1\le i\le n\}$ where L_i is the length of edge e_i, $i=1, 2, \ldots, n$. Let $\Omega_1=\{\omega_{1k}|1\le k\le z_1\}$ be the set of z_1 Class 1 components where ω_{1k} denotes the kth Class 1 component, and $\Omega_2=\{\omega_{2w}|1\le w\le z_2\}$ be the set of z_2 Class 2 components where ω_{2w} denotes the wth Class 2 component. Each component ω_{1k} (resp. ω_{2w}) has multiple states, $1, 2, \ldots, M_{1k}$ (resp. M_{2w}), with corresponding capacities, $0=h_{1k}(1)<h_{1k}(2)<\cdots<h_{1k}(M_{1k})$ for $k=1, 2, \ldots, z_1$ (resp. $0=h_{2w}(1)<h_{2w}(2)<\cdots<h_{2w}(M_{2w})$ for $w=1, 2, \ldots, z_2$), where $h_{1k}(l)$ (resp. $h_{2w}(l)$) is the lth capacity of ω_{1k} (resp. ω_{2w}) for $l=1, 2, \ldots, M_{1k}$ (resp. M_{2w}). Let c_{1k} (resp. c_{2w}) be the allocation cost of component ω_{1k} (resp. ω_{2w}) for $k=1, 2, \ldots, z_1$ (resp. $w=1, 2, \ldots, z_2$). In particular, c_{1k} is the allocation cost per unit of length of component ω_{1k}. That is, the cost of Class 1 component allocation is proportion to its length. Let $B=(b_1, b_2, \ldots, b_{n+q})$ be a two-class allocation (we generally call a component allocation in the rest of this paper), where $b_i=k$ if component ω_{1k} is allocated to e_i for $i=1, 2, \ldots, n$ and $b_i=w$ if component ω_{2w} is allocated to e_i for $i=n+1, n+2, \ldots, n+q$. Then, the computer network under B is a capacitated-flow network. In this study, there should be several assumptions addressed as follows:

(I) Each Class 1 component can be allocated to at most one edge and each edge must contain exactly one Class 1 component.
(II) Each Class 2 component can be allocated to at most one node and each node must contain exactly one Class 2 component.
(III) Flow in (**E**, **N**) must satisfy the flow-conservation law [21].
(IV) The capacities of different components are statistically independent.

3. Problem formulation

3.1. Formulate SR2CAB problem

Let C be an allocation budget. The following constraint says the total cost of component allocation B should not exceed budget C,

$$\sum_{i=1}^{n}\left(c_{1b_i}\cdot L_i\right)+\sum_{i=n+1}^{n+q}c_{2b_i}\le C, \tag{1}$$

where $\sum_{i=1}^{n}\left(c_{1b_i}\cdot L_i\right)$ represents the cost of Class 1 component allocation depending on the edge's length, and $\sum_{i=n+1}^{n+q}c_{2b_i}$ represents the cost of Class 2 component allocation.

Under component allocation B, the maximal capacity of edge (resp. node) e_i denoted by $h_{bi}(M_{bi})$ is equal to $h_{1k}(M_{1k})$ (resp. $h_{2w}(M_{2w})$) if $b_i=k$ (resp. $b_i=w$). In other words, the maximal capacity vector under component allocation B is $(h_{b1}(M_{b1}), h_{b2}(M_{b2}), \ldots, h_{bn+q}(M_{bn+q}))$, designated as $\boldsymbol{M}_B$. Let $X=(x_1, x_2, \ldots, x_{n+q})$ denote a capacity vector where x_i denotes the current capacity of e_i, $i=1, 2, \ldots, n+q$. Any capacity vector X satisfying the following constraint is said to be feasible under B,

$$X\le\boldsymbol{M}_B, \tag{2}$$

where constraint (2) means that the current capacity x_i cannot exceed the allocated component's maximal capacity for $i=1, 2, \ldots, n+q$. For the convenience, let $\mathbf{U}_B$ be the set of such X.

According to the description of the SR2CAB problem, system reliability evaluation under component allocation B is meaningful as the total cost of B meets budget C. Let $V(X)$ be the maximal flow of (**E**, **N**) under X. System reliability under component allocation B denoted by $SR_d(B)$ is defined to be a probability that the maximal flow of (**E**, **N**) is no less than a given demand d, i.e., $SR_d(B)\equiv\Pr\{V(X)\ge d, X\in\mathbf{U}_B\}$. For the convenience, let $\boldsymbol{X}_B=\{X|V(X)\ge d, X\in\mathbf{U}_B\}$, and thus system reliability can be calculated by summing up the probabilities of all $X\in\boldsymbol{X}_B$, i.e., $SR_d(B)=\sum\Pr\{X|X\in\cdot\ \boldsymbol{X}_B\}$. The mathematical programming formulation for the SR2CAB problem is therefore represented as follows:

$$\text{Maximize } SR_d(B)=\sum Pr\{X|X\in\boldsymbol{X}_B\} \tag{3}$$

Subject to

$$b_i=k \quad \text{for i}=1, 2, \ldots, n, \tag{4}$$

$$b_i=w \quad \text{for } i=n+1,\ n+2, \ldots,\ n+q, \tag{5}$$

$$b_i\ne b_j \quad \text{for } i\ne j \text{ and } i, j\in\{1, 2, \ldots, n\}, \tag{6}$$

$$b_i\ne b_j \quad \text{for } i\ne j \text{ and } i, j\in\{n+1, n+2, \ldots, n+q\}, \text{ and} \tag{7}$$

$$\sum_{i=1}^{n}\left(c_{1b_i}\cdot L_i\right)+\sum_{i=n+1}^{n+q}c_{2b_i}\le C. \tag{8}$$