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A dynamic programming approach for layout optimization of interconnection networks

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The reliability and cost are two important performance measures of an interconnection network. Both these aspects need to be attended at the layout design stage for an appropriate trade-off between them. This paper introduces a new approach for layout optimization of interconnection networks using dynamic programming. Our principal objective here is to optimize the network layout so as to maximize the network reliability of a given network within some predefined cost constraint. Since the above problem is NP-hard, a new technique based on dynamic programming is proposed to locate the optimal positions of the nodes and links in the network. The proposed method is illustrated through an example. We also present experimental results for a wide range of interconnection networks. The proposed method is found to be efficient and is applicable for large sized interconnection networks.

1. Introduction

In recent years considerable progress made in the design of VLSI technology has resulted in the emergence of highly powerful processors. The interconnection networks play a vital role in communication among the processing elements. The design and maintenance of such networks are quite difficult [1]. The performance of the interconnection network is mainly judged by ensuring their ability to work even on occurrence of some failures [2]. In other words, the networks must be highly reliable for life critical applications. The design of a network with high reliability involves redundancy and hence increases of cost due to hardware configuration. Therefore, there arises a need to optimize the layout of the network by changing the layout of the nodes and links among them so as to attain high reliability within some predefined cost constraint. Since increase the performance in term of its reliability is closely related to cost, there should be reliability-cost trade off. This trade off can be easily achieved through layout optimization.

The diversity in network structures, resource constraints, and options for reliability improvement has led to construction and analysis of several optimization models viz. reliability optimization problem and redundancy allocation problem [30]. The main objective in reliability optimization problems is to maximize the network reliability subject to overall cost constraint of the network. The review of literature reveals many heuristic approaches to solve such problems. Most of these approaches are based on Artificial Neural Network (ANN) [4] [5], Genetic algorithm (GA) [6–9], Ant colony optimization (ACO) [10], Tabu search [11,12], Simulated annealing [13] and swarm optimization [3]. In Ref. [3], Shi et al. developed a methodology to maximize the load-carrying capacity or strength of composite structures by minimizing the maximum stress. A stochastic global search algorithm called the direct search simulated annealing is employed in the optimization procedure. Beltran et al. [14] used the Tabu Search approach to design a highly reliable network. Their method searches the least cost spanning tree (LCST), where the two-tree objective was a coarse surrogate for reliability. In Ref. [12] the design of a reliable telecommunication network by considering the link constraint as a surrogate for network reliability is discussed. In Ref. [6], Dengiz et al. developed a GA based approach for the optimization of network reliability as a test suit of 20 problems. In Ref. [7], another evolutionary algorithm based on GA approach is proposed for design of a network with minimum cost and certain reliability constraints. However, their

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method is applicable only for networks of very small sizes. Walters et al. [8] used a simple GA approach for structural optimization of pipe networks but they did not consider the capacity and reliability. The authors in Ref. [9] developed a GA based method where they considered average distance, diameter and reliability. The methods in Refs. [5,15] used artificial neural network to estimate the network reliability of interconnection networks. The redundancy allocation at the hardware state is considered as an important option for increasing the reliability of an interconnection network. However, the cost sharply increases with the redundancy. The redundancy allocation problem involves the simultaneous selection of components and a system level design of configuration which can collectively meet all the design constraints in order to optimize some objective function viz. system cost/reliability. Yun et al. [16] proposed a multiple multilevel redundancy allocation problem (MMRAP), where the system and module can be selected simultaneously and the multilevel redundancy is given at the sub system levels. In Ref. [17], Wang et al. considered two fuzzy random redundancy allocation models with bi-objective considerations like reliability maximization and cost minimization. The authors in Ref. [18] proposed a method for modular redundancy allocation optimization in series system and series-parallel systems considering the multilevel reliability configuration. In Ref. [19], Gupta et al. considered the problem of constrained redundancy allocation of series system with interval valued reliability of components. The problem addressed by them was an unconstrained integer programming with interval coefficient by penalty function technique and was meant to maximize the system reliability under limited resource constraints. Li et al. [20] considered the heterogenous redundancy allocation problem for multistate series-parallel systems. They used the Universal Generate Function (UGF) for system reliability estimation and the GA for optimization of system structure. In Ref. [21], Ding et al. also considered the multistate system where they used fuzzy values for performance rates and/or corresponding state probabilities. They used Fuzzy Universal Generating Function (FUGF) for extending the UGF with crisp sets.

The researchers in Ref. [22] discussed the redundancy allocation problem with the objective of maximization of the system reliability in the presence of common cause failures. Li et al. [23] suggested two optimization models which has two mutually conflicting goals like system reliability maximization and minimization of total system cost. They proposed it for the multi-state weighted k-out-of-n system. The task allocation problem and the reliability optimization problem in distributed computing systems is addressed in Ref. [24]. The optimization of series-parallel system with a choice of redundancy strategies using GA approach is considered in Ref. [25]. In Ref. [26], Tian et al. proposed a programming approach for system structure optimization modes using GA. The GA is also used as a tool for optimal resource allocation on grid systems by maximizing service reliability of the system [27]. The study of literature reveals that the value of reliability of a network decreases and its cost increases with increase in the network size. The biggest challenge therefore is to design the most appropriate layout to achieve the maximum reliability within some predefined cost constraints. Such type of design problem can be termed as layout optimization problem [3]. In this paper we address the layout optimization problem and propose a new algorithm based on dynamic programming for solving this problem. We use the concept of dynamic programming here due to its ability to find the exact solution, in contrast to its counter parts techniques [28–30]. The dynamic programming approach always gives a deterministic solution for optimization problems as compared to the near optimal solution in heuristic approaches. The said layout optimization problem is well formulated in this paper. A new algorithm is proposed to find the optimal positions for adding extra nodes along with their links to an existing interconnection network. The proposed algorithm is illustrated by taking a suitable example for better understanding. The convergences of the proposed algorithm along with its important findings are discussed in this paper.

The rest of the paper is organized as follows. The proposed method supported with a mathematical model and an algorithm is presented in Section 2. Our proposed approach is illustrated in Section 3. The application of the proposed method for layout optimization of various kinds of networks and the results obtained are discussed in Section 4. The concluding remarks are presented in Section 5 of the paper.

2. Proposed method

In this section, we formulate the problem and describe the details of the proposed approach using concepts of dynamic programming. The optimization problem is solved through an algorithm. The various symbols and notations used in this paper are given below in Section 2.1.

2.1. Notations

L: Total number of links in the Interconnection Network numbered from 1 to L

N: Total number of nodes in the Interconnection Network numbered from $L + 1$ to $L + N + 1$.

$G(N, L)$: Graph G with N number of nodes and L number of links

$G'(N', L')$: Graph G' having N' number of nodes and L' number of links (after adding n number of nodes and $2n$ number of links)

C_0: Initial cost of the interconnection network before optimization

C_{ij}: Cost of the link connecting node i to node j

C_k: Cost of the node k

C_{max}: Maximum permissible cost of the Interconnection Network

(i, j): Link between nodes i & j

X: Link topology of $\{x_{1,1}, x_{1,2}, \ldots, x_{i,j}, \ldots, x_{N-1,\ N}\}$

$x_{i,j}$: A decision variable indicating whether the nodes in G are connected or not; $x_{i,j} = 1$, if nodes i and j are connected, otherwise $x_{i,j} = 0$ ($x_{i,j} \in X$)

x_i: A decision variable to indicate whether there is a link between the nodes $(i, N + 1)$, for $i = 1, 2, 3, \ldots, N$ ($x_i \in X$).

R: Network reliability of interconnection network

$R(X)$: Network reliability of X

R_0: Initial network reliability of the Interconnection Network before optimization

T_u: uth spanning tree of graph G

$d(N_i)$: Degree of node N_i

RM: Reliability matrix of G

CM: Cost matrix of G

p_l, p_N: Link reliability and node reliability of the interconnection network respectively

$N_{1\ldots N}$: Nodes to be added to the Interconnection Network for optimization

$LR_{1\ldots 2N}$: Reliability matrix of $2N$ number of links to be added to the Interconnection Network for optimization

$NR_{1\ldots N}$: Reliability matrix of N number nodes to be added to the Interconnection Network for optimization

$LC_{1\ldots 2N}$: Cost matrix of $2N$ number of links to be added to the Interconnection Network for optimization

$NC_{1\ldots N}$: Cost matrix of N number nodes to be added to the Interconnection Network for optimization