Some Combinatorial Optimization Schemes for Multi-Layer Network Topology

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Abstract - The article addresses combinatorial optimization schemes for design of multi-layer communication network topology. The paper consists of three parts: (a) description of system issues as basic requirements, trends (e.g., evolution, upgradeability), and a "system space" for contemporary network design; (b) brief description of some basic combinatorial optimization problems as follows: multicriteria ranking, knapsack-like problems, clustering, morphological combinatorial synthesis, assignment / allocation problem; and (c) advanced combinatorial optimization design schemes (e.g., design of two-layer bi-connected topology, allocation of cross-links and "bridges", direct network formation, upgrade of networks via improvement of existing nodes / links and allocation of additional nodes / links). The combinatorial optimization schemes are considered as some combinations of combinatorial optimization problems above.

Keywords— **Multi-layer networks, Communication network topology, Design schemes, Combinatorial optimization, Decision making**

I. INTRODUCTION

The article focuses on design of multi-layer communication network topology on the basis of combinatorial optimization problems (multicriteria ranking, knapsack problems, clustering, allocation problems, morphological combinatorial synthesis) ([2], [3], [5], [6], [8], [9], [23], [26], [43], etc.). Network topology has a central role in network design [12], [15], [21], [22], [27], [31], [32], [39], [40], [41], [42], [43], etc.). Now significance of multi-layer multi-region communication networks is increasing ([4], [12], [25], [27], [32], [39], etc.). Here a system approach to the analysis and design of the communication networks is examined including network hierarchy, system requirements, issues of upgradeability, and advanced design problems for bi-connected networks and some their versions with additional nodes / links. The network improvement processes are considered on the basis of the following actions ([7], [15], [25], [29], [31], [38], [40], [43], etc.): (a) improvement of existing components (i.e., nodes, links), (b) addition and allocation of new components (i.e., links, nodes), and (c) design of a new network topology (including revelation of several layers).

II. SYSTEM ISSUES

A. Network Hierarchy

Traditional network hierarchy consists of the following layers: (a) international (multi-country, continent) network GAN; (b) metropolitan network MN; (c) wide area network WAN; and (d) local area network LAN. *IBM Red Book* contains an interesting dimensional classes of networks by node numbers as follows: (i) large size communication network ($>$ 500 nodes); (ii) medium size communication network ($<$ 500 nodes); and (iii) small size communication network ($<$ 80 nodes) [30]. From the "engineering" viewpoint, hierarchical layers involve the following:
1. Backbone network.
2. Global network segment as a set of interconnected network segments including the following: (a) additional centers, (b) cross-connections, and (c) bridges.
3. Access network / network segment (cluster): bi-connected topology (about 20 nodes).
4. Distributed network: a simple hard topology (e.g., bus, tree, ring).
As a result, a class of small-dimensional networks is added to the above-mentioned classification: 20 ... 25 nodes. Here a simplified network hierarchy is examined as follows :
1. TOP LAYER: nodes and links for connection of clusters: 1.1 basic node clusters (network segments), 1.2 communication centers, 1.3 cross-connection links (center's connection), and 1.4. links for connection of neighbor clusters.
2. MEDIUM LAYER: basic clusters (network segment/ access networks, bi-connected topological modules).
3. BOTTOM LAYER: distribution networks (e.g., tree, ring, bus).
Thus the following problems are considered: (a) design of bi-connected topology (medium layer) and (b) design of network topology at the top layer (i.e., multi-layer bi-connected topology with additional nodes / links).

B. Requirements / Criteria

The following main system requirements corresponding to the above-mentioned network hierarchical layers

are examined:
1. Top layer: 1.1. safety (stability, reliability, redundancy, survivability); 1.2. manageability, adaptability, flexibility; 1.3. upgradeability; 1.4. cost; and 1.5. closeness to a GRID-environment.
2. Medium layer: 2.1. basic quality; 2.2. reliability; and 2.3. survivability.
3. Bottom layer: 3.1. basic quality (time, cost, etc.) and 3.2. reliability.
In addition, it is reasonable to point out contextual classification of the requirements as follows:
Part 1. 'User' requirements: 1.1. time (start stage, communication stage); 1.2. quality (information errors, reliability of connection); and 1.3. cost.
Part 2. System requirements: 2.1. cost; 2.2. reliability, stability, redundancy (k-connection, etc.); 2.3. manageability; 2.4. maintainability; 2.5. testability; 2.6. modularity; 2.7. adaptability (e.g., to geographical distribution of users); 2.8. safety (terrorist attacks, etc.); and 2.9. flexibility (e.g., reconfigurability).
Part 3. Requirements for mobile networks.
Part 4. System evolution / development requirements: 4.1. possibility for re-design (upgradeability); 4.2. possibility for multi-stage re-design (multi-stage upgradeability); and 4.3. closeness to a future resultant network environment (e.g., a multi-layer GRID).

C. Basic Generations of Network Topology

The following basic generations for network topology phases are considered:
Phase 1. Simple spanning structures: minimal cost spanning tree, minimal Steiner tree.
Phase 2. Bi-connected structures: special graphs.
Phase 3. Survivable networks: special structures (usually, bi-connected structures with additional links).
Phase 4. A multi-layer GRID-like environment: Flexible, upgradeable network, reconfigurable topology.
Here our design problems are oriented to phases 3 and 4 above.

D. "System Space" for Design

In the paper, a generalized "system space" for design is considered as follow:
1. Number of nodes: (a) < 20, (b) (20...80), (c) (80...500), and (d) > 500.
2. Functions: (a) distribution, (b) access, (c) communication, and (d) global communication.
3. Geography: (a) LAN, (b) WAN, (c) Metropolitan, and (d) International.
4. Topology configuration: (a) simple topology (e.g., bus, tree, ring), (b) bi-connected network, (c) survivable network (e.g., additional cross links, "bridges"), (d) a multi-layer GRID-like environment.
5. Requirements: (a) "user-centered" criteria (quality, cost), (b) "system-centered" criteria (e.g., self-organization, flexibility, manageability, stability, reliability), and (c) "development / evolution centered" criteria (e.g., mobility, upgradeability).
6. Design approaches: (a) selection of design solutions, (b) one-criterion optimal design, (c) multicriteria optimization / decision making, and (d) macro-heuristics based on multicriteria design frameworks.

III. SUPPORT COMBINATORIAL MODELS

A. Multiple Criteria Ranking

The problem is the following. Let $V = \{1, ..., i, ..., p\}$ be a set of items which are evaluated upon criteria $K = 1, ..., j, ..., d$ and $z_{i,j}$ is an estimate (quantitative, ordinal) of item i on criterion j. The matrix $\{z_{i,j}\}$ can be mapped into a partial order on V. The following partition as linear ordered subsets of V is searched for:

$$V = \cup_{k=1}^{m} V(k), \ |V(k_1) \cap V(k_2)| = 0 \ \ if \ \ k_1 \neq k_2,$$

$$i_2 \preceq i_1 \ \ \forall i_1 \in V(k_1), \ \forall i_2 \in V(k_2), \ k_1 \leq k_2.$$

Set $V(k)$ is called layer k, and each item $i \in V$ gets priority r_i that equals the number of the corresponding layer.
The list of basic techniques for multicriteria selection is the following [5]: (1) multi-attribute utility analysis [17]; (2) multi-criterion decision making [18] and multicriteria optimization [37]; (3) Analytic Hierarchy Process (AHP) [34]; (4) outranking techniques [33]; etc.

B. Knapsack Problem

The basic problem is ([9], [26], etc.):

$$\max \quad \sum_{i=1}^{m} c_i x_i$$

$$s.t. \quad \sum_{i=1}^{m} a_i x_i \leq b, \quad x_i = 0 \cup 1, \ i = 1, ..., m$$

and additional resource constraints $\sum_{i=1}^{m} a_{i,k} x_i \leq b_k; \ k = 1, ..., l;$ where $x_i = 1$ if item i is selected, for ith item c_i is a value ("utility"), and a_i is a weight. Often nonnegative coefficients are assumed. The problem is NP-hard ([9], [26]) and can be solved by enumerative methods (e.g., Branch-and-Bound, dynamic programming) approximate schemes with a limited relative error ([26], etc.).
In the case of a multiple choice problem, the units (e.g., actions) are divided into groups and we select elements from each group while taking into account a total resource constraint (or constraints).

C. Clustering

Clustering problem is a basic scientific problem in many domains ([2], [3]):
Divide an initial set of elements into groups (subsets, clusters) to minimize the ”distances” (or proximities) between elements in the clusters (i.e., ”intercluster distances”).
The following data can be used as initial information: (a) parameters of each element and / or (b) proximity (”distance”) between elements. The problem is close to the above-mentioned multicriteria ranking but without the order over the set of obtained subsets. In network design and management, clustering is used to get local subsystems (e.e., areas). Basic clustering algorithms (agglomerative algorithm, etc.) are described in ([2], [3], [11], [14]). Often polynomial heuristics are used (e.g., agglomerative algorithm). In mobile networking, organization of networks is based on the following stages [16]: (i) clustering of nodes, (ii) selection (location) of clusterheads, and (iii) design of a communication topology for clusterheads. Thus clustering is an important part of approaches to network topology design.

D. Morphological Combinatorial Synthesis

Here morphological combinatorial synthesis consists in morphological design. We use Hierarchical Morphological Multicriteria Design (HMMD) on the basis of morphological clique problem [23]. The examined composite (modular, decomposable) system consists of components and their interconnection (Is) or compatibility. Basic assumptions of HMMD are the following: *(a)* a tree-like structure of the system; *(b)* a composite estimate for system quality that integrates components (subsystems, parts) qualities and qualities of Is (compatibility) across subsystems; *(c)* monotonic criteria for the system and its components; *(d)* quality of system components and Is are evaluated on the basis of coordinated ordinal scales. The designations are: (1) design alternatives (DAs) for leaf nodes of the model; (2) priorities of DAs ($r = 1, ..., k$; 1 corresponds to the best one); (3) ordinal compatibility (Is) for each pair of DAs ($w = 0, ..., l$, l corresponds to the best one). The basic phases of HMMD are: *1.* design of the tree-like system model; *2.* generation of DAs for leaf nodes of the model; *3.* hierarchical selection and composing of DAs into composite DA's for the corresponding higher level of the system hierarchy; *4.* analysis and improvement of composite DAs (decisions). Let S be a system consisting of m parts (components): $P(1), ..., P(i), ..., P(m)$. A set of design alternatives is generated for each system part above. The problem is:
Find a composite design alternative $S = S(1) \star ... \star S(i) \star ... \star S(m)$ of DAs (one representative design alternative $S(i)$ for each system component / part $P(i)$, $i = 1, ..., m$) with non-zero Is between design alternatives.
A discrete space of the system excellence on the basis of the following vector is used: $N(S) = (w(S); n(S))$, where $w(S)$ is the minimum of pairwise compatibility between DAs which correspond to different system components (i.e., $\forall\ P_{j_1}$ and P_{j_2}, $1 \leq j_1 \neq j_2 \leq m$) in S, $n(S) = (n_1, ..., n_r, ...n_k)$, where n_r is the number of DAs of the rth quality in S. As a result, we search for composite decisions which are nondominated by $N(S)$. Thus, the following layers of system excellence can be considered: (i) ideal point; (ii) Pareto-effective points; (iii) a neighborhood of Pareto-effective DAs (e.g., a composite decision of this set can be transformed into a Pareto-effective point on the basis of an improvement action(s)). Clearly, the compatibility component of vector $N(S)$ can be considered on the basis of a poset-like scale too (as $n(S)$). In this case, the discrete space of system excellence will be an analogical lattice. Figs. 1 and 2 illustrate the composition problem. In the example, composite DAs is: $S_1 = X_2 \star Y_1 \star Z_2$, $N(S_1) = (2; 2, 0, 1)$.

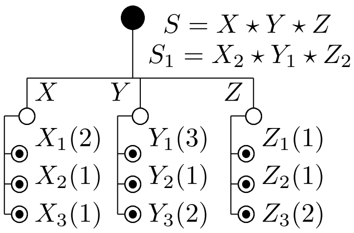

Fig. 1. Example of composition

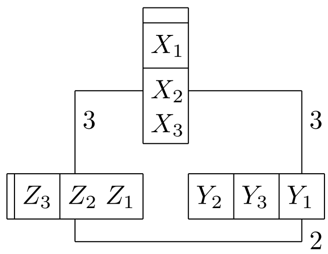

Fig. 2. Concentric presentation

E. Allocation Problem

Location and allocation problems are widely used in many domains ([6], [8], etc.). In network design, allocation of network resources (e.g., communication and / or computer resources) is a basis. Mainly allocation problem is formulated as follows: (a) simple assignment problem (polynomial solvable), (b) multiple choice problem (NP-hard), (c) quadratic assignment problem (NP-hard), (d) matching problem (polynomial solvable for bipartite graph), (e) the stable marriage problem (polynomial solvable), (f) vertex coloring problem (NP-hard), etc. Application of various types of allocation models (mathematical programming approach) in network design is described in [16].

E.1 Simple Assignment Problem

Simple assignment problem involves correspondence matrix $A = ||a_{ij}||$ where a_{ij} is a profit to assign element i to position j. The problem is ([9], etc.):
Find the assignment $\pi = (\pi(1), ..., \pi(n))$ *of elements to positions which corresponds to a total effectiveness:* $\sum_i \pi_{i\pi(i)} \rightarrow \max$.
Note *minmax* objective function can be used too. This problem is a balanced transportation problem and can be solved efficiently, for example, on the basis of Hungarian method ([20], etc.). Note this problem is the matching problem for bipartite graphs ([9], etc.).

E.2 Quadratic Assignment Problem

More complicated well-known model (QAP) includes interconnection between elements of different groups (each group corresponds to a certain position) ([6], etc.). Note the use of QAP for facility layout planning has been proposed many years ago [19]. So, we consider a generalization of multiple-choice knapsack problem by taking into account additive profits of item compatibility. Let a nonnegative value $d(i, j_1, k, j_2)$ be a profit of compatibility between item j_1 in group J_i and item j_2 in group J_k. Also, this value of compatibility is added to the objective function. Such quadratic programming problem is:

$$\max \quad \sum_{i=1}^{m} \sum_{j=1}^{q_i} c_{i,j} x_{i,j} +$$

$$\sum_{l<k} \sum_{j_1=1}^{q_l} \sum_{j_2=1}^{q_k} d(l, j_1, k, j_2) x_{l,j_1} x_{k,j_2}$$

$$l = 1, ..., m; \ k = 1, ..., m$$

$$s.t. \quad \sum_{i=1}^{m} \sum_{j=1}^{q_i} a_{i,j} x_{i,j} \leq b$$

$$\sum_{j=1}^{q_i} x_{i,j} \leq 1; j = 1, ..., m$$

$$x_{i,j} = 0 \cup 1; \ i = 1, ..., m; \ j = 1, ..., q_i.$$

The quadratic assignment problem is NP-hard. The following algorithms are often used for the problem: (1) Branch-And-Bound methods, (2) heuristics, for example, genetic approach ([36], etc.), tabu search ([35], etc.).

E.3 Allocation on Binary Relations

Let us briefly describe allocation as mapping of a set of elements (F) into a set of possible *positions* (D) [24]: $F \Rightarrow D$. Often it is reasonable to take into account binary relations on elements and positions. Thus allocation problem on binary relations can be considered as a generalization of morphological model [23] and stable marriage problem ([10], [28], etc). The following binary relations can be used:
(a) *proximity*: on $(F \times F)$: R_1, on $(D \times D)$: R_2;
(b) *correspondence*: on $(F \times D)$ (symmetrical): R_3, on $(F \rightarrow D)$: R_3^F, and on $(D \rightarrow F)$: R_3^D.
Thus the problem is:
Find mapping (allocation) $X : F \Rightarrow D$ while taking into account the best realized *correspondence* and saving *proximity* R_1 on R_2.
Evidently, the central problem formulation issue is the following: measurement of the above-mentioned *correspondence* and *proximity*. Fig. 3 illustrates allocation on binary relation. In [23] this kind of allocation problem is reduced to morphological design.

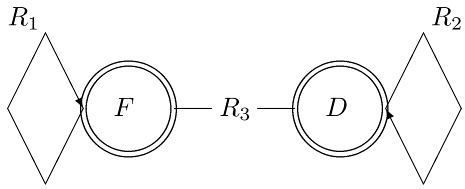

Fig. 3. Allocation over binary relations

E.4 Advanced Problem Formulation

From the practical viewpoint, the following generalizations of the allocation problems are prospective ones: (i) improvement of allocation solutions, (ii) reallocation, (iii) extension of allocation solutions, and (iv) multistage allocation (or dynamical allocation).

IV. ADVANCED DESIGN SCHEMES

A. Design of Two-Layer Bi-Connected Topology

The special 2-connected topology with two centers (each of them is a 3-node clique) was suggested in [42]. Here our combinatorial solving scheme is oriented to the design of this kind of bi-connected topology:
Step 1. Multicriteria ranking of nodes (set $A = B \cup C$, $|B| = 6$) on the basis of some criteria (importance, useful placement, etc.) to obtain a rank for each node. (Methods of multicriteria analysis are described in [5]).
Step 2. Forming of two "centers" (three-node cliques) on the basis of six nodes (set $B \subseteq A$) with the best ranks above. (It is assumed $2 \leq |C|$) .

Step 3. Usage of two knapsack problems ([9], [26]) for connection of each node (set C) to a node of "center 1" and to a node of "center 2".

Fig. 4 illustrates the problem. Note here it is possible to consider a new formulation of the problem when initial six node-candidates (all or part) are some additional nodes. This problem is an analogue of Minimal Steiner Tree Problem (i.e., approximation of a network by usage of some additional nodes) ([13], [23]).

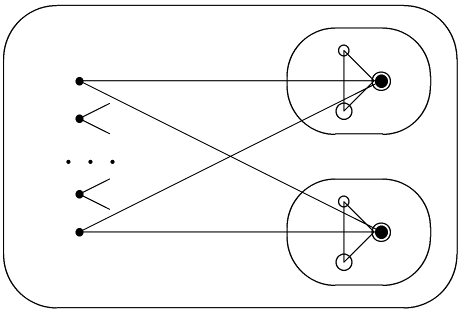

Fig. 4. Illustration for 2-connected network

B. Allocation of Cross-Links and "Bridges"

The both problems (allocation of cross-links and / or bridges) provide for obtaining some kinds of more reliable / survivable networks ([1], etc.). In this case, solving scheme is the following:

Step 1. Generating a set of candidates for additional cross-links (and / or bridges).

Step 2. Selection of resultant cross-links (and / or bridges) (here the following models can be used: multicriteria selection, knapsack problem, multicriteria knapsack problem, morphological combinatorial synthesis [23].

C. Direct Network Formation

Direct network formation is often under examination. Usually, knapsack-like models are used for this problem. At the same time, morphological combinatorial synthesis is an evident formulation of this kind of network design problem. In this case, each node-pair is examined as a part of the resultant composite decision:

Step 1. Generating some alternative versions (design alternatives DAs) for connection of each pair of nodes.

Step 2. Generating possible intersection of the alternative versions above (e.g., common parts of the paths).

Step 3. Evaluation of the DAs and their compatibility (via their possible intersections).

Step 4. Solving the obtained morphological combinatorial synthesis problem to get the resultant decision.

D. Extended Re-Design / Upgrade of Topology

Extended re-design (improvement / upgrade) of network topology can be based on the following basic actions: (i) addition and allocation of new nodes, (ii) improvement (up-grade) of old nodes, (iii) addition and allocation of new links, (iv) improvement (up-grade) of old links, and (v) building of a new topology (at various layers). Thus the following solving schemes are examined:

Scheme 1: Addition of new nodes and / or links.

Scheme 2: Improvement of some existing nodes and / or links.

Scheme 3: Joint addition & improvement (integration of scheme 1 and 2).

Scheme 4: Design of a new topology.

The following approaches are considered for the abovementioned solving schemes: an engineering analysis, multicriteria analysis and selection, knapsack-like problems including multicriteria knapsack, allocation problems (including basic assignment problem, quadratic assignment problem, some kinds of multicriteria assignment problems), morphological combinatorial synthesis problem.

V. CONCLUSION

In this paper, system analysis of to-day's trends in the field of network topology design is applied and several advanced combinatorial design problems are described. Our suggestions are based on some new kinds of modern design approaches which involve composite frameworks, multicriteria decision making, and morphological combinatorial synthesis. Thus, the study leads to a set of interconnected (by data, by formulations, and by solving schemes) design problems and can be considered as a basis for a new computer-aided tool for network design and improvement (upgrade).

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