Integrated Genetic Algorithm and Goal Programming for Network Topology Design Problem With Multiple Objectives and Multiple Criteria

Chen-Shu Wang and Ching-Ter Chang

***Abstract*—Network topology design (NTD) with multiple objectives has been presented by many researchers. However, no work in the literature has addressed this issue with both multiple objectives and multiple criteria. In order to suit real-world situations, this paper presents a new idea integrating genetic algorithm and goal programming to establish a model for solving the NTD problem with multiple objectives and multiple criteria taken into consideration. In addition, the proposed model can also solve both construct and extend network topology problems under shared risk link group (SRLG) constraints. Finally, illustrative examples are included to demonstrate the superiority and usefulness of the proposed method.**

***Index Terms*—Genetic algorithm (GA), goal programming, network topology design (NTD).**

I. Introduction

An IMPORTANT issue of communication networks is to find an appropriate network topology for obtaining good telecommunication quality, balancing system reliability, optimal related costs, and fitting the network's applications [1], [7], [12], [13], [15], [17], [19], [22], [24], [27]. However, network topology design (NTD) is a typical NP-complete problem, which can only be solved by heuristic techniques (such as greedy heuristic, genetic algorithm, and simulated annealing technique) with a modest number of nodes [12], [15], [17], [19]. In the past two decades, many works have devoted to solving NTD problem with multiple objectives (NTD-MO).

However, the existing solutions of NTD-MO are still insufficient to satisfy the network designer's requirement because the characteristics of each node within the network are quite different [1] and these objectives usually conflict with one another. Thus, multiple criteria and multiple objectives should be considered at the same time when solving the problem of NTD. NTD-MO can be divided into two categories: the "construct problem of NTD (CNTD)" and "extend problem of NTD (ENTD)." CNTD deals with constructing a whole new topology in communication network and ENTD deals with THE link enhancement problem for an existing communication network.

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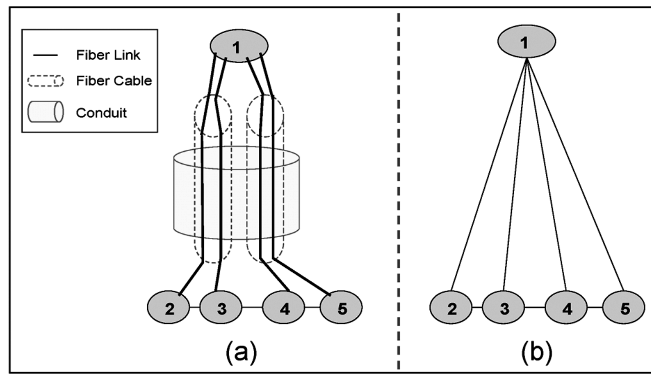

Fig. 1. Fiber topology.

Most previous studies have dealt separately with the problem of CNTD and ENTD [2], [6], [12], [20]. The characteristics of the related works in the literature are summarized in Table I. In this paper, we propose a general model (GM), which can be easily applied to these two problems.

The practical demands provide us the motivation to solve NTD with multiple objectives and multiple criteria (NTD-MOMC) instead of solving NTD-MO alone. NTD-MOMC is a good aid for decision-makers when solving MOMC problems to suit real-world situations. Furthermore, in large-scale optical networks, a wavelength channel has a transmission rate larger than gigabits per second. If the channel fails, a lot of connection streams in the channel will be dropped. Thus, many protection algorithms have been proposed for solving the problem. However, conventional protection algorithms assume that the fiber links in A communication network are independent of each other [9]. In fact, fiber links interconnecting network nodes are often routed over common sections of fiber or conduit [9], [23]. Therefore, some fiber links in actual networks have corrected failures, as shown in Fig. 1.

The fiber cable and conduit topology is shown in Fig. 1(a), and the corresponding fiber link topology is shown in Fig. 1(b). Notably, the fiber links 1-2, 1-3, 1-4, and 1-5 are independent of each other in the fiber link topology shown in Fig. 1(b). However, fiber links 1-2 and 1-3 traverse a common fiber cable in the actual network shown in Fig. 1(a). The breakdown of fiber cable can lead to the simultaneous failure of fiber links 1-2 and 1-3. Even though the fiber links 1-2 and 1-5 traverse different fiber cables in Fig. 1(a), simultaneous failure of these links due to these fiber cables may still traverse a common conduit. The above-mentioned idea is called shared risk link group (SRLG)

TABLE I
RELATED WORKS OF NTD-MO

Proposed methods	The characteristics of proposed methods
Jan, Hwang and Cheng [11]	To solve CNTD problem with reliability and cost objectives
Kumar, Pathak and Gupta [12]	To solve ENTD problem with diameter, average distance, degree, and reliability objectives
Palmer and Kershenbaumt [19]	To solve optimal minimal cost spanning tree problem
Elbaum and Sidi [7]	To solve CNTD problem with network capacity, packet delay cost objectives
Ko, Tang, Chan, Man and Kwong [13]	To solve CNTD problem with packet delay, reliability, the bi-connected of node, cost, and network traffic objectives
Saha and Chakraborty [22]	To solve ENTD problem with performance and cost objectives
Ahmed and Bakry [1]	To solve ENTD problem of GULFNET with users' characteristics, population, economic growth, and network traffic objectives
Berry, Murtagh, McMahon, Sugden and Welling [2]	To solve CNTD problem with work traffic and cost objectives
Zhou and Gen [27]	To solve CNTD problem with cost, time of construct, complexity, and reliability objectives
Liu and Iwamura [15]	To solve CNTD problem with multiple reliability goals
Liu [14]	To solve CNTD problem with packet delay, cost and network capacity objectives
Zalesky, Vu, Zukerman, and Ouveysi [26]	To solve CNTD problem with minimizing the maximum level of congestion

problem [9]. In order to suit real-world situations, the SRLG constraints should be considered in the model of NTD-MOMC. By doing so, this paper proposes a GM, which integrates genetic algorithm (GA) and goal programming (GP) to solve the NTD-MOMC problem in which both CNTD and ENTD problems with SRLG constraints are considered. We adopted GP for inferring and modeling of the GM and applied GA to the problem as a search tool for the GM to obtain the near-optimal solutions. In addition, compared with the method of Liu and Iwamura [15] for solving the NTD-MO problems, the proposed method can obtain better solutions. Two advantages of the GM are listed below.

1) It can be easily applied to NTD-MOMC problems and it can also solve both CNTD and ENTD problems to suit real-world situations.
2) The SRLG constraints that require modeling large-scale networks are considered.

The remainder of this paper is organized as follows. Section II defines the problem. Mask mechanism is discussed in Section III, and GM is detailed in Section IV. Solution process of GM using GA is shown in Section V. The numerical experiments are given in Section VI. Section VII offers conclusions and directions for future research.

TABLE II
RELATED WORKS OF NTD-MO

Negative related objective	Proposed	Positive related objective.	Proposed
Average Distance	[12] [27]	Budget	[6] [20]
Requirement	[13] [19]	Performance	[6] [20]
Complexity	[27]	Profit	[6] [20]
Cost	[12] [19] [27]	Reliability	[2] [12] [15] [27] [20]
Number of Nodes	[11] [20]	Network Capacity	[12] [13]
Diameter	[12] [27]	Routing	[13]
Message Delay	[1] [13] [12]	Linking Degree	[12]

II. PROBLEM DEFINITION

A. Network Topology Design

Node and link are two major components of computer network. The computer network can be represented by a graph $G = (V, E)$, where V represents the set of nodes (or vertices) and E represents the set of links (or edges). NTD-MO has received great attention in the field of NTD optimization [1], [7], [12], [13], [19], [22], [27]. In Table II, we extracted the primary features from previous studies and classified these features into two types: the "positive-related objective" and "negative-related objective." Whether the features are positive or negative depends on the computer network performance. For instance, the reliability of node rises with increasing number of links from other nodes connected to the node in the computer network. This in turn enhances the computer network performance. Thus, to increase the number of links can be regarded as a case of positive-related objective. On the contrary, saving cost is negatively related to computer network performance, which should be regarded as a case of negative-related objective. With reference to the concept of positive-related and negative-related objective, we propose a mask mechanism for treating both CNTD and ENTD problems in Section III.

B. Notation Definition

Notations used in this paper are given here.

OP_i — Reliability of fiber link in level i of SRLG, $i = 1, 2, \ldots, l$.

TT — Target topology represented by an undirected graph.

V — Set of n nodes (vertices).

C_{ij} — Connected cost from node i to node j.

X_{ij} — 0–1 variable, defined as $\begin{cases} 1, & \text{node } i \text{ is connected to node } j \\ 0, & \text{otherwise} \end{cases}$.

Req_{ij} — Capacity of the fiber link between node i and node j.

K — $K \subseteq V$, K is the subset of v.

$\Theta(K,TT)$	Reliability of subset K under given TT.
$\omega(TT)$	Total cost of TT.
$\rho(K,TT)$	The network capacity of subset K under given TT.
$\Phi(K,TT)$	Linkage degree of subset K under given TT.
$\mathrm{Rel}_r(K)$	Setting criteria of reliability within subset K, $r=1,2,\ldots,m$.
$Cap_p(K)$	Setting criteria of network capacity within subset K, $p=1,2,\ldots,t$.
$Deg_d(K)$	Setting linkage degree criteria of vector, $d=1,2,\ldots,q$.
B	Total available budget.
W_{Bug}	Setting weighting factor for the budget objective.
W_{Deg}	Setting weighting factor for the linkage degree objective.
W_{Rel}	Setting weighting factor for the reliability objective.
W_{Cap}	Setting weighting factor for the network capacity objective.
$R_r^+(R_r^-)$	Positive (negative) deviation from the setting reliability goal.
$D_d^+(D_d^-)$	Positive (negative) deviation from the setting linkage degree goal.
$p_p^+(p_p^-)$	Positive (negative) deviation from the network capacity goal.
$b^+(b^-)$	Positive (negative) deviation from the budget objective.
P	Population size of each generation of GA.
C	Crossover rate of GA.
F(i)	Fitness value of ith population.

C. Network Topology Design—Multiple Objectives and Multiple Criteria

In this research, we consider an NTD-MOMC problem that involves optimizing four objectives, such as cost, reliability, network capacity, and linkage degree. In addition, we can arbitrarily assign multiple criteria such as reliability, network capacity, and linkage degree to each objective according to the requirements of DMs. The mathematical formulation of the NTD-MOMC is given below.

(NTD-MOMC)

Given: A budget B

Find out: The optimal target topology (TT) subject to the multiple objectives ($\omega(TT)$, $\Phi(K,TT)$, $\Theta(K,TT)$, $\rho(K,TT)$) and multiple criteria ($Deg_d(K)$, $\mathrm{Rel}_r(K)$, $Cap_p(K)$, $d=1,2,\ldots,q$, $r=1,2,\ldots,m$, $p=1,2,\ldots,t$)

All functions and parameters used in the NTD-MOMC are listed below:

The cost objective: $\omega(TT)$

For each candidate TT, the total cost should be expressed as follows:

$$\omega(TT)=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}C_{ij}X_{ij} \tag{1}$$

Reliability objective: $\Theta(K,TT)$

We assume that all nodes in the computer network are perfectly reliable and fiber links fail stochastic independently with known probabilities if the fiber links do not traverse a common fiber cable or conduit. In contrast, if the fiber links traverse a common fiber cable or conduit, then they fail simultaneously with known probabilities. Without loss of generality, we classified fiber cables and conduits into several reliability levels, OP_i, according to real-world situations. The success of communication between nodes in subset K under given TT is a random event. The probability of this event is called the K nodes reliability, denoted by $\Theta(K,TT)=\Pr$ {the probability that any pair of nodes in subset K under given TT can communicate with each other}. It is almost impossible to design an algorithm to compute $\Theta(K,TT)$ analytically [16]. To solve this problem, we employed the Monte Carlo simulation algorithm which involves repeating stochastic independently M trials. The algorithm can randomly generate an operational TT^* according to the value of OP_i. We next describe the Monte Carlo algorithm.

While $(Counter \leq M)$

{

For ($i=1$ to the number of SRLG reliability levels)
Randomly drop an operational link from TT to obtain an operational TT^* according to $(1-OP_i)$

Next i;

If $\Theta(K,TT^*)$ is K-connected, then M'++ Counter++

};

$\Theta(K_m,TT)=M'/M$;;

The network capacity objective: $\rho(K,TT)$

For simplicity, but without loss of generality, we assume that the network topology and traffic load are known in advance. Asymmetrical traffic matrix is applied to the network. The capacities of fiber links should be implemented to satisfy all traffic loads in each pair of nodes [24]. The following matrix can represent the traffic of fiber links:

$$\begin{vmatrix}\mathrm{Req}_{11} & \mathrm{Req}_{21} & \cdots & \mathrm{Req}_{i1}\\ \mathrm{Req}_{12} & \mathrm{Req}_{22} & \cdots & \mathrm{Req}_{i2}\\ \vdots & \vdots & \vdots & \vdots\\ \mathrm{Req}_{1j} & \mathrm{Req}_{2j} & \cdots & \mathrm{Req}_{ij}\end{vmatrix}$$

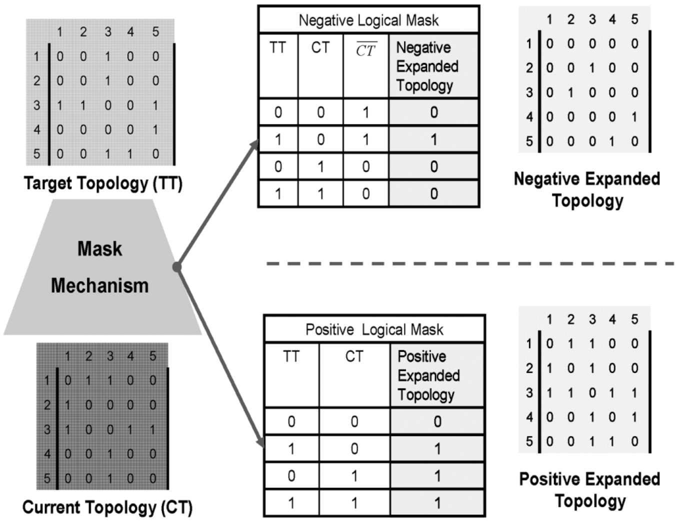

Fig. 2. Mask mechanism.

where the traffic of the fiber link between $node_i$ and $node_j$ is denoted by Req_{ij}. The traffic matrix is asymmetrically distributed (i.e., Req_{ij} may be (not) equal to Req_{ji}) due to different properties of nodes.

III. Mask Mechanism

Classical methods usually treat CNTD and ENTD as distinct problems and solve them separately as shown in Table I. However, sometimes we expect to have an integrated optimization approach that can treat both CNTD and ENTD problems at the same time. In order to achieve this objective, one optimization approach with mask mechanism is then proposed as follows.

The behavior of the mask mechanism involves two types of logical operations, namely the "positive logical mask" and "negative logical mask" shown in Fig. 2. The behavior of positive logical mask (negative logical mask) is the same as OR (AND)-gate logical operation. For positive-related objective (negative-related objective) case, we use positive logical mask (negative logical mask) to mask TT and $CT(\overline{CT})$ to produce a positive expanded topology (negative expanded topology). Then, the fitness of TT is evaluated according to the value of positive expanded topology (negative expanded topology). As seen in Fig. 2, the above procedure involves $\text{positive expanded topology} = TT + CT$ and $\text{negative expanded topology} = TT \bullet \overline{CT}$, where $+$ is a logical "OR" operation and $\bullet$ is a logical "AND" operation.

In the ENTD case, there does exist a CT, thus the mask mechanism can be easily employed to evaluate TT from CT. On the other hand, in the CNTD problem, there does not exist a CT, thus we can regard CT as a $v \times v$ dimension of zeros-matrix. Then, mask mechanism can also be easily applied to the CNTD problem. According to the above-mentioned information, the GM using the mask mechanism as an integrated method can treat both CNTD and ENTD problems. In order to demonstrate how to evaluate the fitness of TT using positive expanded topology (negative expanded topology) for negative-related objective (positive-related objective), we take a process of ENTD for instance to explain the behavior of the mask mechanism. Suppose we want to evaluate the fitness of TT using cost and reliability as shown in Fig. 2. Take column 3 in TT as [1 1 0 0 1] to show that negative logical mask and positive logical mask can be used to mask this column to obtain negative expanded topology as $[1\ 1\ 0\ 0\ 1] \bullet [0\ 1\ 1\ 0\ 0] = [0\ 1\ 0\ 0\ 0]$ and positive expanded topology as $[1\ 1\ 0\ 0\ 1] + [1\ 0\ 0\ 1\ 1] = [1\ 1\ 0\ 1\ 1]$. While we use negative expanded topology (positive expanded topology) to replace TT because the cost(reliability) is a kind of negative-related objective (positive-related objective). Similar to ENTD, in the CNTD case, the negative expanded topology and positive expanded topology are both obtained as [1 1 0 0 1] because CT is a 5×5 dimension of zeros-matrix (i.e., $\text{negative expanded topology} = [1\ 1\ 0\ 0\ 1] \bullet [1\ 1\ 1\ 1\ 1] = [1\ 1\ 0\ 0\ 1]$ and $\text{positive expanded topology} = [1\ 1\ 0\ 0\ 1] + [0\ 0\ 0\ 0\ 0] = [1\ 1\ 0\ 0\ 1]$). Then, we can evaluate the fitness of TT according to the estimated value of negative expanded topology and positive expanded topology. Hence, the fitness of TT can be estimated accurately through the mask mechanism in both ENTD and CNTD problems. Notably, the mask mechanism can translate the CNTD problem to become a special case of ENTD problem. Thus, we can solve them in the same optimization model in Section IV.

IV. General Model

There are three assumptions in GM: 1) TT can be represented by a graph G; 2) a graph G does not have any self-loop; and 3) failure of a fiber link is stochastic independent of failures of other links if the fiber links do not traverse a common fiber cable or conduit with one another. Otherwise, it has corrected failure with other fiber links if they traverse a common fiber cable or conduit. There are mainly two ways to formulate NTD-MOMC [19]. One is the cost-oriented approach that aims to minimize total cost subject to MOMC performance constraints. We formulate NTD-MOMC using the cost-oriented approach as follows:

P1

$$\text{Min} \quad \omega(TT) \le B$$

Subject to

$$\Phi(K, TT) \ge \mathrm{Deg}_d(K), \quad d = 1, 2, \ldots, q \tag{2}$$

$$\Theta(K, TT) \ge \mathrm{Rel}_r(K), \quad r = 1, 2, \ldots, m \tag{3}$$

$$\rho(K, TT) \ge \mathrm{Cap}_p(K), \quad p = 1, 2, \ldots, t. \tag{4}$$

Equation (2) is multiple degree criteria constraints, (3) is multiple reliability criteria constraints, and (4) is multiple capacity criteria constraints.

The other approach is a performance-oriented method that maximizes the performance of a computer network subject to real-world constraints (e.g., cost and reliability). We formulate NTD-MOMC using the performance-oriented method as follows:

P2

$$\text{Max} \quad \Phi(K, TT) + \Theta(K, TT) + \rho(K, TT)$$

Subject to

$$\omega(TT) \le B \tag{5}$$

$$(2) - (4). \tag{6}$$

The GP is a good aid in modeling multiple objective decision-making problems. It was first introduced by Charnes and Cooper [4] and further developed by Tamiz *et al.* [25], Romero [21] and Chang [3]. It has been accomplished using various types of approaches such as Lexicographic GP, Weight GP, MINMAX (Chebyshev) GP and Multi-choice GP [3]. In order to enable DMs to easily set the weighting for each objective according to their preference, we adopted the Weight GP approach to translate P2 into the proposed model given as

Proposed Model

$$Min \quad W_{Bug}b^- + W_{Deg}\sum_{d=1}^{q}\left(D_d^-\right) + W_{\mathrm{Rel}}\sum_{r=1}^{m}\left(R_r^-\right) + W_{Cap}\sum_{p=1}^{t}\left(P_p^-\right)$$

Subject to

$$\omega(TT) + b^+ - b^- = B \tag{7}$$

$$\Phi(K,TT) - D_d^+ + D_d^- = Deg_d(K), \quad d=1,2,\ldots,q \tag{8}$$

$$\Theta(K,TT) - R_r^+ + R_r^- = \mathrm{Rel}_r(K), \quad r=1,2,\ldots,m \tag{9}$$

$$\rho(K,TT) - P_p^+ + P_p^- = Cap_p(K), \quad p=1,2,\ldots,t \tag{10}$$

$$b^+, b^-, D_d^+, D_d^-, R_r^+, R_r^-, P_p^+, P_p^- \geq 0, \quad d=1,2\ldots,q \;\; r=1,2,\ldots m \;\; p=1,2,\ldots,t. \tag{11}$$

Finally, we introduce the concept of mask to proposed model to obtain the GM as follows:

GM

$$\mathrm{Min} \quad W_{\mathrm{Bug}}b^- + W_{\mathrm{Deg}}\sum_{d=1}^{q}\left(D_d^-\right) + W_{\mathrm{Rel}}\sum_{r=1}^{m}\left(R_r^-\right) + W_{\mathrm{Cap}}\sum_{p=1}^{t}\left(P_p^-\right)$$

Subject to

$$\omega(NET) + b^+ - b^- = B \tag{12}$$

$$\Phi(K,\mathrm{PET}) - D_d^+ + D_d^- = \mathrm{Deg}_d(K), \quad d=1,2,\ldots,q \tag{13}$$

$$\Theta(K,\mathrm{PET}) - R_r^+ + R_r^- = \mathrm{Rel}_r(K), \quad r=1,2,\ldots,m \tag{14}$$

$$\rho(K,\mathrm{PET}) - P_p^+ + P_p^- = \mathrm{Cap}_p(K), \quad p=1,2,\ldots,t \tag{15}$$

$$b^+, b^-, D_d^+, D_d^-, R_r^+, R_r^-, P_p^+, P_p^- \geq 0, \quad d=1,2\ldots,q \;\; r=1,2,\ldots m \; p=1,2,\ldots,t \tag{16}$$

where NET represents the negative expanded topology via the process of negative mask, and PET represents the positive expanded topology via the process of positive mask.

V. Solution Process of GM—Using GA

In the 1970s, Holland developed the GA, which is a stochastic searching method for optimization problems using the mechanics of natural selection. GA is developed from the theory of survival in nature [8]. Since GA is a very good stochastic technique for tackling combinatorial optimization problems, we adopt GA with mask mechanism as the search tool for GM, which is shown in Fig. 3.

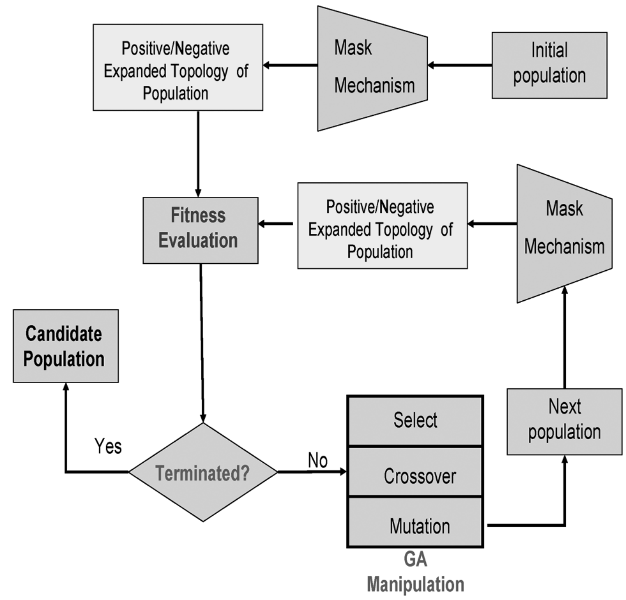

Fig. 3. Solution process of GM using GA.

As can be seen, an initial population of solution is randomly created. Then, using mask mechanism, such as negative logical mask and positive logical mask yields a masked population (i.e., positive expanded topology/negative expanded topology population). The fitness of each individual determines whether it will survive or not. Terminated criteria (such as the generation size or the gap between objectives) are then adopted to determine the optimal TT to be achieved. Finally, by using genetic operators such as selection, crossover and mutation, the next generation is obtained. After a number of iterations or predefined criteria are met, it is hoped that a near optimal solution can be found.

A. *Representation Structure: Encode/Decode*

A communication network is represented by an undirected graph, which can be expressed by a two-dimensional matrix. In the graph, each edge has two states: operational and failed. We use $n(n-1)/2$ bits string as chromosome to represent TT. The encode/decode equation (i.e., vector to matrix/vice verse) is defined as in (1) as follows:

$$TT = \begin{bmatrix} 0 & X_{2,1} & X_{3,1} & \cdots & X_{n-1,1} & X_{n,1} \\ & 0 & X_{3,2} & \cdots & X_{n-1,2} & X_{n,2} \\ & & 0 & \vdots & \vdots & X_{n,3} \\ & & & 0 & X_{n-1,n-2} & \vdots \\ & & & & 0 & X_{n,n-1} \\ & & & & & 0 \end{bmatrix}$$

$$X_{i,j} = V_{\frac{(2n-i)(i-1)}{2}+j-1} \quad \forall \quad 1 < i < n-1, \quad \forall \quad i+1 \leq j \leq n. \tag{17}$$

B. Evaluation Function

We revise the objective function of GM as an evaluation function of GA, denoted by $F(i)$. The evaluation function of GA can be expressed as (18) because the lower the objective value of GM, the higher the fitness of GA will be

$$F(i) = \frac{1}{W_{\text{Bug}}b^{-}+W_{\text{Deg}}\sum_{d=1}^{q}\left(D_d^{-}\right)+W_{\text{Rel}}\sum_{r=1}^{m}\left(R_r^{-}\right)+W_{\text{Cap}}\sum_{p=1}^{t}\left(P_p^{-}\right)} \tag{18}$$

where all variables are defined as in GM.

C. GA Manipulations

Selection: Roulette wheel selection is employed to ensure that highly fit chromosome has a greater number of offsprings. In this mechanism, a candidate network is selected according to its survival probability, which is equal to its relative fitness with respect to the whole population as

$$\left[\frac{F(i)}{\sum_{i\in p}F(i)}\right]. \tag{19}$$

Crossover: Crossover operator selects two chromosomes from the mating pool at random for mating work, and a crossover site C is selected at random in the interval $[1, n(n-1)/2]$. Two new chromosomes, called offsprings, are then obtained by swapping all characters between position C and $n(n-1)/2$.

Mutation: The combined operations of reproduction and crossover may sometimes lose some potentially useful information from the chromosomes. To overcome this drawback, mutation is then introduced. It is implemented by complementing a bit (0 to 1 and vice versa) at random. This ensures that good chromosomes are not permanently lost.

VI. Numerical Experiments and Analysis

Here, we present a CNTD-MO experiment for comparison with that of Liu and Iwamura [15]. In addition, for further verification, we revised experiment 1 to be an ENTD problem shown in experiment 2. Finally, we testified NTD-MOMC problem with SRLG constraints shown in experiment 3 to demonstrate the usefulness of the GM. All of the experiments are formulated by GM and solved by MATLAB [18] on a PC with CPU 2.6 GHz.

A. Experiment 1: 10-Node CNTD-MO

The GM with a simulation-based GA has been written in MATLAB for topological optimization problem. In order to demonstrate the superiority of the GM, we consider a 10-node fully connected network adopted from Liu and Iwamura [15]. Parameters are given as follows. The population size is 200.

TABLE III
MO Constraints of Experiment 1

Multiple Object	
Budget	$\omega(TT)$ =250 (210) for case I (II)
Degree	$\Phi(K,TT) = Deg_1(K) = 2$, $K = (1,2,...10)$
Reliability	$\Theta(K,TT) = \text{Re}l_1(K) = 0.99$, $K = (1,3,6,7)$ $\Theta(K,TT) = \text{Re}l_2(K) = 0.95$, $K = (2,4,5,9)$ $\Theta(K,TT) = \text{Re}l_3(K) = 0.90$, $K = (1,2,3,4,5,6,7,8,9,10)$

TABLE IV
Cost Matrix of Experiment 1

	1	2	3	4	5	6	7	8	9	10
1	-	30	43	45	50	62	25	15	51	45
2		-	26	76	45	25	46	45	15	25
3			-	38	17	30	30	13	45	45
4				-	35	28	16	20	10	15
5					-	15	25	37	34	37
6						-	38	40	10	40
7							-	36	46	16
8								-	42	24
9									-	45
10										-

The generation size is 100 (600) for Case I (II). The probability of crossover is 0.3. The probability of mutation is 0.2. MO constraints are given in Table III. Cost matrix is given in Table IV. The operational probabilities of all links are 0.9. The total available budget is 250 (210) for Case I (II). The weight of each objective is 1.

According to GM, we formulate experiment 1 as follows:

P3

$$\text{Min}\quad b^{-}+\sum_{d=1}^{q}\left(D_d^{-}\right)+\sum_{r=1}^{m}\left(R_r^{-}\right)\quad d=1, r=1,2,3$$

Subject to

$$\omega(TT)+b^{+}-b^{-}=250(210). \tag{20}$$

The total available budget for case I (II) is

$$\Theta(K,TT)-R_r^{+}+R_r^{-}=\text{Re}l_r(K),\ \ r=1,2,\ldots,3 \tag{21}$$

$$\Phi(K,TT)-D_d^{+}+D_d^{-}=2,\ \ d=1, \tag{22}$$

$$b^{+},b^{-},D_d^{+},D_d^{-},R_r^{+},R_r^{-}\geq 0,\ \ d=1\ \ r=1,2,\ldots 3. \tag{23}$$

The GM is employed to solve P3 with about 25 (30) generations for Case I (II) shown in Figs. 4 and 5, which can satisfy three predefined goals. The results of TT are obtained as shown in Tables V and VI, and the total cost is 240 (188) for Case I (II).

The comparison of Liu and Iwamra's solution [15] and P3's solution is shown in Table VII. As can be seen, a 0.08 reliability gap exists between $\text{Rel}_2(K)$ and $\text{Rel}_3(K)$. For P3, in contrast, all MO constraints are fully satisfied without any gap existing

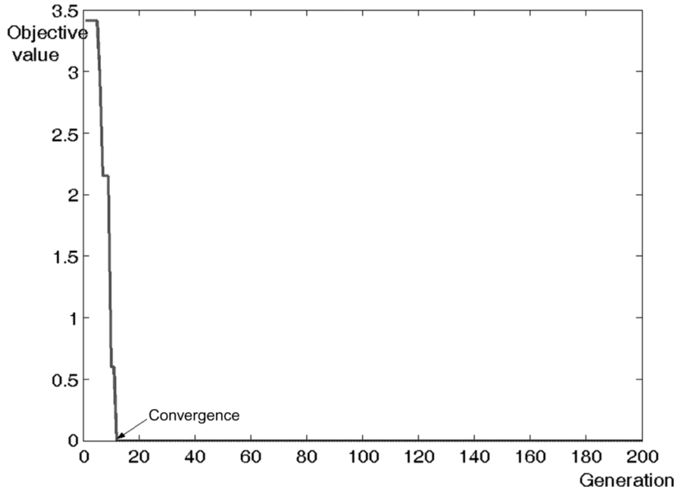

Fig. 4. Convergence of TT in Case I.

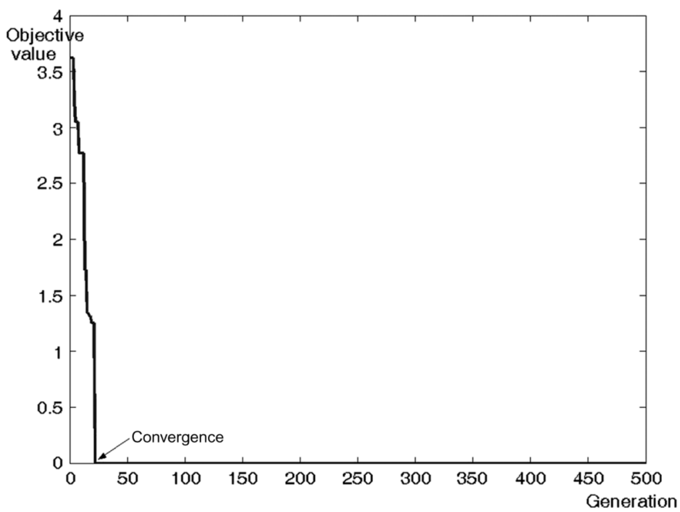

Fig. 5. Convergence of TT in Case II.

TABLE V
TT OF CASE I WITH ABOUT 25 GENERATIONS

	1	2	3	4	5	6	7	8	9	10
1	-	1	0	0	0	0	1	1	0	0
2		-	0	0	0	1	0	0	0	1
3			-	0	1	0	0	1	0	0
4				-	0	0	1	0	1	1
5					-	1	0	0	0	0
6						-	0	0	1	0
7							-	0	0	0
8								-	0	1
9									-	0
10										-

in $\mathrm{Rel}_i(K)$. It is interesting to note that P3 not only can solve a higher number of links (i.e., $Deg_1(K) = 13$) using less cost (188), but can also completely satisfy all MO constraints.

B. Experiment 2: The Enhanced Function of MOMC

In order to demonstrate the enhanced function of MOMC, we try to solve the link enhancement problem of experiment 1.

TABLE VI
TT OF CASE II WITH ABOUT 30 GENERATIONS

	1	2	3	4	5	6	7	8	9	10
1	-	0	0	0	0	0	1	1	0	0
2		-	1	0	0	0	0	0	0	1
3			-	0	1	0	0	1	0	0
4				-	0	0	1	0	1	0
5					-	1	0	0	0	0
6						-	0	0	1	0
7							-	0	0	1
8								-	0	0
9									-	0
10										-

TABLE VII
COMPARISON OF LIU AND IWAMURA'S SOLUTION AND P3'S SOLUTION

	Generation Size	Total cost	$Deg_1(K)$	None Bi-connect
Liu and Iwamura (2000) [15]	100 (case I)	242	11	1,7
	600 (case II)	210	12	-
P3	about 25	240	11	-
	about 30	188	13	-

(a)

	$\mathrm{Re}l_1(K)$	$\mathrm{Re}l_2(K)$	$\mathrm{Re}l_3(K)$
Liu and Iwamura (2000) 15]	0.99	0.87	0.75
	0.991	0.956	0.938
P3	1	1	1
	1	1	1

(b)

Parameters are given as follows. MOMC constraints are given in Table VIII. The total available enhanced budget is 100. Other parameters are defined as in experiment 1.

We take the result of experiment 1 as CT. Then, we formulate this problem to be P4 with mask mechanism. The mask mechanism produces positive expanded topology and negative expanded topology for evaluating the objective value as follows:

P4

$$\mathrm{Min} \quad (b^-) + \sum_{d=1}^{q} (D_d^-) + \sum_{r=1}^{m} (R_r^-) \quad d = 1,2 \;\; r = 1,2,3$$

Subject to

$$\omega(NET) + b^+ - b^- = B \tag{24}$$

$$\Phi(K, \mathrm{PET}) - \mathrm{D_d^+} + \mathrm{D_d^-} = \mathrm{Deg_d(K)}, \quad \mathrm{d} = 1,2 \tag{25}$$

$$\Theta(K, \mathrm{PET}) - R_r^+ + R_r^- = \mathrm{Rel}_r(K), \quad r = 1,2,3 \tag{26}$$

$$b^+, b^-, D_d^+, D_d^-, R_r^+, R_r^- \geq 0, \quad d = 1,2, \quad r = 1,2,3. \tag{27}$$

The GM is employed to solve P4 with about 30 generations. The result of TT is obtained as shown in Table IX and the total cost of TT is 70. As can be seen from Table IX, two more new linkages marked by square brackets are added to TT. The performance analysis of TT is shown in Table X.

TABLE VIII
MOMC CONSTRAINTS OF EXPERIMENT 2

	Multiple Object
Budget	$\omega(TT)$ =250 (210) for case I (II)
Degree	$\Phi(K,TT)=Deg_1(K)=2$, $K=(1,2,...10)$
Reliability	$\Theta(K,TT)=\mathrm{Re}l_1(K)=0.99$, $K=(1,3,6,7)$ $\Theta(K,TT)=\mathrm{Re}l_2(K)=0.95$, $K=(2,4,5,9)$ $\Theta(K,TT)=\mathrm{Re}l_3(K)=0.90$, $K=(1,2,3,4,5,6,7,8,9,10)$
	Multiple Criteria
Degree	$\Phi(K,TT)=Deg_1(K)=2$, $K=(1,3,5,7,9)$ $\Phi(K,TT)=Deg_2(K)=3$, $K=(2,4,6,8,10)$
Reliability	$\Theta(K,TT)=\mathrm{Re}l_1(K)=0.99$, $K=(1,3,6,7)$ $\Theta(K,TT)=\mathrm{Re}l_2(K)=0.98$, $K=(2,4,5,9)$ $\Theta(K,TT)=\mathrm{Re}l_3(K)=0.95$, $K=(1,2,3,4,5,6,7,8,9,10)$

TABLE IX
TT OF EXPERIMENT 2 IN GENERATION 200

	1	2	3	4	5	6	7	8	9	10
1	-	1	0	0	0	0	1	1	0	0
2		-	0	0	0	1	0	0	0	1
3			-	0	1	0	0	1	0	0
4				-	0	0	1	0	1	1
5					-	1	0	0	1	0
6						-	0	0	1	0
7							-	0	0	1
8								-	0	1
9									-	0
10										-

TABLE X
PERFORMANCE ANALYSIS OF TT

	Generation Size	Total cost	$Deg_1(K)$	$Deg_2(K)$
Experiment 1	13	240	2	2.5
P4	15	310	2.8	3.2

(a)

	$\mathrm{Re}l_1(K)$	$\mathrm{Re}l_2(K)$	$\mathrm{Re}l_3(K)$
Experiment 1	1	1	1
P4	1	1	1

(b)

C. Experiment 3—SRLG Constraints

In order to demonstrate the feasibility of the GM, SRLG constraints are considered as a reliability issue for NTD-MOMC problem. Parameters are given as follows.

1) There are three kinds of failure of links are fiber link, fiber cable, and conduit.

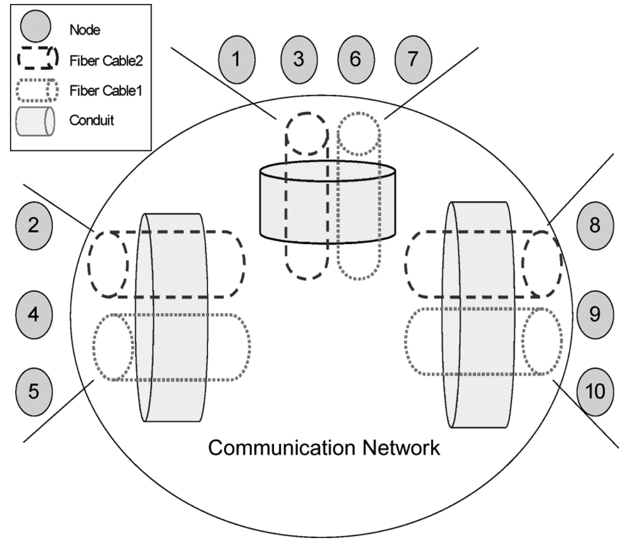

Fig. 6. Initial topology of SRLG.

TABLE XI
MOMC CONSTRAINTS OF EXPERIMENT 3

	Multiple Object
Budget	$\omega(TT)$ =250
Degree	$\Phi(K,TT)=Deg(K)=2$, $K=(1,2,...,10)$
Capacity	$p(K,TT)\geq \mathrm{Re}\,q_{i,j\in K}$, $K=(1,2,...,10)$
Reliability	$\Theta(K,TT)=r-criteria\,setting$, $r=(1,2,3)$
	Multiple Criteria
Reliability	$\Theta(K,TT)=\mathrm{Re}l_1(K)=0.99$, $K=(1,3,6,7)$ $\Theta(K,TT)=\mathrm{Re}l_2(K)=0.95$, $K=(2,4,5,9)$ $\Theta(K,TT)=\mathrm{Re}l_3(K)=0.90$, $K=(1,2,3,4,5,6,7,8,9,10)$
	Objectives Weights
Budget	$W_{Bug}=5$
Degree	$W_{Deg}=3$
Capacity	$W_{Cap}=1$
Reliability	$W_{Rel}=2$

2) The operational probabilities of links in the level of SRLG, OP_i, are given as: $OP_1 = \text{fiber link} = 0.9$, $OP_2 = \text{fiber cable} = 0.93$, and $OP_3 = \text{conduit} = 0.95$.
3) There are three shared link groups, all nodes within the group traverse a common conduit. Shared link group 1 contains nodes 1, 3, 6, and 7, shared link group 2 contains nodes 2, 4, 5, and 9, and shared link group 3 contains nodes 8 and 10. Each conduit contains two types of fiber cables where fiber cable 1 is of 30 Mbps and fiber cable 2 is 50 Mbps. The initial topology of SRLG is shown in Fig. 6.
4) MOMC constraints are shown in Table XI. Cost matrix is given in Table IV. The end-to-end capacity requirements are depicted in Table XII.

TABLE XII
END-TO-END TRAFFIC REQUIREMENTS (Mbps)

	1	2	3	4	5	6	7	8	9	10
1	-	35	10	12	20	8	25	7	15	10
2		-	20	5	6	15	12	6	7	12
3			-	13	18	10	5	17	13	6
4				-	9	5	9	13	30	20
5					-	15	14	25	3	8
6						-	21	4	20	3
7							-	2	5	19
8								-	18	2
9									-	3
10										-

TABLE XIII
TT OF EXPERIMENT 3 WITH 200 GENERATIONS

	1	2	3	4	5	6	7	8	9	10
1	-	1	0	0	0	0	1	0	0	0
2			1	0	0	0	0	0	0	0
3			-	0	1	0	0	0	0	0
4				-	0	0	0	0	1	1
5					-	1	0	1	0	0
6						-	0	0	1	0
7							-	0	0	1
8								-	1	0
9									-	0
10										-

TABLE XIV
FIBER CABLE ASSIGNMENT OF TT

	1	2	3	4	5	6	7	8	9	10
1	-	2	0	0	0	0	1	0	0	0
2	2	-	2	0	0	0	0	0	0	0
3	0	2	-	0	1	0	0	0	0	0
4	0	0	0	-	0	0	0	0	2	1
5	0	0	1	0	-	2	0	2	0	0
6	0	0	0	0	2	-	0	0	1	0
7	2	0	0	0	0	0	-	0	0	1
8	0	0	0	0	2	0	0	-	1	0
9	0	0	0	2	0	1	0	2	-	0
10	0	0	0	1	0	0	1	0	0	-

According to GM and SRLG constraints, we formulate this problem as follows:

P5

$$\text{Min} \quad 5(b^-) + 2\sum_{d=1}^{1}\left(D_d^-\right) + 3\sum_{r=1}^{3}\left(R_r^-\right) + (P^-)$$

Subject to

$$\omega(TT) + b^+ - b^- = 250 \tag{28}$$

$$\Theta(K, TT) - R_r^+ + R_r^- = \text{Re}l_r(K), \quad r = 1, 2, 3, \tag{29}$$

$$p(K, TT) - P^+ + P^- = \text{Re}q_{i,j\in K}, \tag{30}$$

$$\Phi(K, TT) - D_d^+ + D_d^- = 2, \quad d = 1 \tag{31}$$

$$b^+, b^-, D_d^+, D_d^-, R_r^+, R_{r,}^- P^+, P^- \geq 0,$$

$$r = 1, 2, 3, \quad d = 1. \tag{32}$$

The GM is employed to solve P5 with 200 generations. The result of TT is obtained as shown in Table XIII and the total cost of TT is 243. In addition, the assignment of fiber cable is shown in Table XIV, where $X_{ij} = 1(2)$ presents the fiber link assigned to fiber cable 1(2). The near-optimal TT of experiment 3 is shown in Fig. 7.

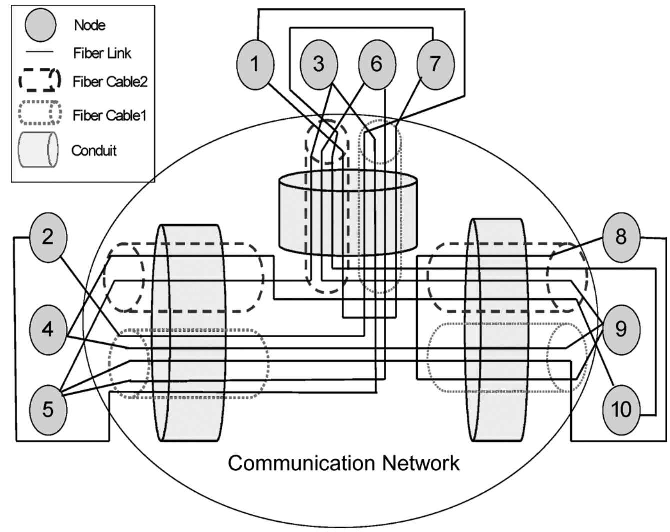

Fig. 7. Actual topology of SRLG experiment.

TABLE XV
PERFORMANCE ANALYSIS OF TT

Total linkage degree	Total cost	$Deg(K)$	$\text{Re}l_1(K)$	$\text{Re}l_2(K)$	$\text{Re}l_3(K)$
11	243	2	0.95	0.95	0.90

The performance analysis of TT is shown in Table XV. There is a 0.04 (i.e., 0.99-0.95) reliability gap of $\text{Re}l_1(K)$ and SRLG constraints are satisfied. All nodes are bi-connected and some of them used different fiber cables to achieve the reliability requirement of ensuring that a message can use backup paths to reach the destination. For instance, node 9 can directly reach node 6 or pass another path through nodes 8 and 5 to reach node 6.

D. Computation Experiment

The superiority of the proposed GM model can also be observed through the larger scale (50 nodes) examples. Thus, a set of test problems is formed. Each of the test examples is formulated as NTD_MO problem by the proposed GM model. There are given objectives includes: three budget levels (2000, 2500 and 3000), two reliability levels ($\text{Re}l_1(1, 3, \ldots, 49) = 0.95$ for all odd nodes and $\text{Re}l_2(2, 4, \ldots, 50) = 0.99$ for all even nodes) and all nodes have to be bi-connected ($Deg_1(1, 2, \ldots, 50) \geq 2$). In addition, for each budget level, five groups of the cost matrix and networking capacity requirement data are randomly generated. Hence, a set of 15 test problems is formed and then each problem solved by Matlab [18] for 100 generations on a PC/586. The average CPU time of 15 experiments is about 45 minutes. As the result given in Table XVI shows, there is an average reliability gap of 18.42% and 76 linkage degrees when the budget is limited to 2000 and a 5.79% reliability gap and 88 linkage degrees when the budget is limited to 2500. Furthermore, there is only 0.32% gap within reliability objective when the budget is 3000 and the linkage degree is 115.

TABLE XVI
COMPARISON SOLUTION WITH LARGER SCALE PROBLEMS

Budget	Average cost	$Deg_1(K)$	$\mathrm{Re}l_1(K)$	$\mathrm{Re}l_2(K)$
2000	1945.50	76	0.8768	0.8790
2500	2336.00	89	0.9388	0.9433
3000	2905.50	115	0.9760	0.9868

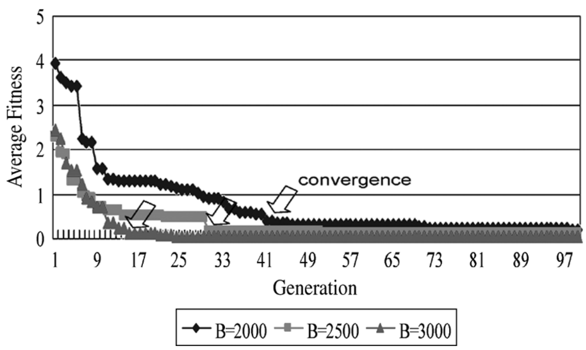

Fig. 8. Convergence of TT.

TABLE XVII
COMPARISON OF GM AND PERVIOUS RESEARCHES

	Kumar (1995)	Liu and Iwamura (2000)	Ko et al. (1997)	Ahmed and Bakry (1997)	GM (2006)
Scopes	CNTD	CNTD	CNTD	ENTD	CNTD & ENTD
Object TYPE	MO	SO	MO	MO	SO &MO
Criteria TYPE	SC	MC	SC	SC	SC &MC
Extend able	Enable without weight setting	Disable	Enable without weight setting	Disable	Enable with weight setting

As the results show, consistent with the reasonable inference, while the budget is sufficiently abundant (e.g., 3000 of this test experiment), the gap of objectives is decreasing. Hence, GM takes contradictory objectives into consideration simultaneously and provided fittest solution to decision maker in advance than networking actually deployment. In addition, as the results have shown, while the MO constraints are looser (e.g., budget), the convergence rate of fitness value is faster in Fig 8. As the result, the proposed GM model can be applied to larger scale NTD problems.

VII. CONCLUSION

NTD-MOMC is closer to realistic NTD in the real world. In this paper, we propose a GA-based generalized model to solve both the CNTD-MOMC and ENTD-MOMC problems. A variety of solutions are summarized in Table XVII.

As seen from Table XVII, GM is the best solution for NTD optimization problems because it can solve NTD with any types of constraints such as MO, single objective multiple criteria (SOMC), and MOMC. In addition, GM can find a near-optimal network topology under SRLG constraints. Our future research will focus on other applications and further verification of GM.

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