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2005

Wang, Y., Cheng, T. H., & Lim, M. H. (2005). A tabu search algorithm for static routing and wavelength assignment problem. IEEE Communications Letters. 9(9), 841-843.

<https://hdl.handle.net/10356/90761>

<https://doi.org/10.1109/LCOMM.2005.1506721>

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A Tabu Search Algorithm for Static Routing and Wavelength Assignment Problem

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Abstract—Static routing and wavelength assignment (RWA) is usually formulated as an optimization problem with the objective of minimizing wavelength usage (MWU). Existing solution methodologies for the MWU problem are usually based on a two-step approach, where routing and wavelength assignment are done independently. Though this approach can reduce computational cost, the optimality of the solution is compromised. We propose a novel *tabu search* (TS) algorithm, which considers routing and wavelength assignment jointly without increasing the computational complexity. The performance of the proposed TS algorithm is compared with the *Integer Linear Programming* (ILP) method, which is known to solve the MWU to optimality. The results for both small and large networks show that our proposed TS algorithm works almost as well as the ILP solution and is much more computationally efficient.

Index Terms—Minimum wavelength usage, tabu search, static routing and wavelength assignment, optical network.

I. INTRODUCTION

IN THE context of optical networks, a lightpath is an all-optical channel trail, which originates and ends at a pair of access nodes of the network and may span across multiple fiber links [1]. When there is no wavelength converter in the network, a lightpath uses the same wavelength along the trail. Finding a lightpath involves finding a route and assigning a wavelength to the route. This is generally dubbed *routing and wavelength assignment* (RWA) problem. An important area in RWA is the *minimum wavelength usage* problem (MWU) [1]–[3]. For this problem, a set of requests for a given optical network is assumed to be known *a priori* and each of the known requests needs to be assigned a lightpath. A constraint of this problem is that no two assigned lightpaths should be assigned the same wavelength on the same link since each wavelength on each link can only be used by one lightpath. The objective of the MWU is to minimize the number of wavelengths used if there is no cap on the number of wavelengths during the planning stage. The MWU can be formulated as an optimization problem. In [1], [2], the *Integer Linear Programming* (ILP) approach is used to find a global optimum solution for the MWU problem. Based on the relaxation of integer variables in the ILP formulations, different techniques are used to find near optimal solutions for large networks when finding exact solutions are too computationally intensive. These techniques include randomized rounding [1] and column generation [2]. Due to the computational intensity of the ILP approach,

heuristic algorithms, which are widely applied in solving various combinatorial optimization problems, have begun to surface as alternatives. In [3], an evolutionary algorithm is proposed. In [4], a *tabu search* (TS) algorithm is designed to solve the RWA problem of scheduled lightpath requests, which is analogous to the MWU problem described here. Both algorithms are effective when applied to a small network. We notice that both [3] and [4] essentially follow the two-step approach of [1] in solving the RWA problem. In the two-step approach, the MWU problem is decoupled into two sub-problems, which are solved separately in sequence. First, the routes of the requests are found by means of an ILP based algorithm [1], evolutionary algorithm [3] or [4]. Secondly, wavelength assignment is carried out by a graph coloring algorithm. In the ILP approach, this method significantly reduces the number of integer variables in the formulation, and can significantly improve the computation efficiency at the expense of optimality. However, we notice that when TS is applied, the complexity of the algorithm is mainly governed by the neighborhood selection of the search process instead of the whole search space, which is proportionate to the number of variables. In view of this, we propose a tabu search algorithm, which considers route and wavelength assignment jointly. Our simulation study for a relatively large network of 50 nodes shows that the results are almost as good as that yielded by the ILP solution. The proposed TS algorithm can solve the MWU problem within half an hour while the ILP solution takes more than a day to find the solution.

II. PROPOSED TABU SEARCH ALGORITHM

TS is an iterative procedure that starts with an initial solution and repeatedly constructs new solutions by searching the neighborhoods of the current solution. Each solution has an associated neighborhood $N(\Gamma)$, a subset of the whole solution space Φ . The step by which solution $\Gamma' \in N(\Gamma)$ is reached is called a move. A cost function $C(\Gamma)$ is formulated to evaluate the fitness of the current solution in relation to the objective of the TS. For each iteration, the Γ' with the best $C(\Gamma')$ is selected as the new current solution. The process continues to generate neighboring solutions until the *stopping criterion* is satisfied. In order to avoid revisiting solutions already encountered, a tabu list is maintained. The list contains a number of the latest selected solutions, which should not be chosen for a certain number of subsequent iterations. This mechanism allows for escape from the local minima and sometimes a jump to a new search region. For detailed description of a generic TS algorithm, interested readers may refer to [5].

To describe the MWU problem, we use variable L_i to

Manuscript received January 29, 2005. The associate editor coordinating the review of this letter and approving it for publication was Dr. Ivan Fair.

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Digital Object Identifier 10.1109/LCOMM.2005.09001.

represent a lightpath assigned to a request $R_i \in \Delta$, where $\Delta = \{R_1, R_2, \dots, R_m\}$ is the given set of requests. The value of L_i is represented by a pair (p_i, w_i) , where p_i is a route from R_i 's source node s_i to destination node d_i on the given directed network, and w_i is the wavelength assigned to that route. If each variable is assigned a value, we call this set of assignment $\{(p_1, w_1), (p_2, w_2), \dots, (p_m, w_m)\}$ a solution Γ to the MWU problem. If there are no two assigned lightpaths in Γ sharing the same link and using the same wavelength; i.e., no lightpaths are in conflict with each other, solution Γ is dubbed a *feasible solution*.

To find a *feasible solution* with minimum wavelength usage, our proposed algorithm starts with a relatively large set of available wavelengths W . If the algorithm can find a *feasible solution* with $|W|$ wavelengths using the TS subroutine, the cardinality of W is reduced by one, and the TS subroutine is run again. The iteration ends when the algorithm is no longer able to find a feasible solution with certain W , and returns $|W|+1$ as the result. The initial available wavelength set W is obtained by the *first fit* algorithm proposed in [3].

The TS subroutine is designed to find a feasible solution with a given W . The problem-specific details of the TS approach are described below:

- 1) Let P_i denote the candidate paths set associated to R_i . P_i is pre-calculated using the k -shortest paths algorithm in [6]. The initial solution Γ_{ini} is constructed by randomly assigning a $p_i \in P_i$ and a $w_i \in W$ to each variable L_i .
- 2) The cost function $C(\Gamma)$ is computed as:

$$C(\Gamma) = \sum_i^{|\Delta|} C_i \quad (1)$$

A conflict cost C_i is associated with each variable L_i and is calculated as the number of conflicts the assigned lightpath of L_i experienced in the current solution. For example, in a solution $\Gamma = \{(p_1, w_1), (p_2, w_2), (p_3, w_3)\}$, if (p_1, w_1) is in conflict with (p_2, w_2) and (p_3, w_3) , $C_1 = 2$. If (p_1, w_1) is not in conflict with any other lightpath in Γ , $C_1 = 0$. Clearly, Γ is a *feasible solution* if and only if the total number of conflicts $C(\Gamma) = 0$.

- 3) The neighborhood $N(\Gamma)$ of the current solution is constructed in the following way. A *conflict request list* (CRL) is maintained in the whole TS subroutine. The CRL is derived from Γ_{ini} ; specifically, CRL is derived from Γ_{ini} by noting the L_i whose $C_i > 0$. We denote the first variable (*head*) in the CRL as L_f . A neighbor Γ' of Γ is constructed by assigning a new value to L_f while keeping all other variables of Γ unchanged.
- 4) CRL is updated at the end of each iteration. For each iteration, a neighbor Γ' with the best $C(\Gamma')$ is found to replace the current solution Γ . We use Ω_f to represent the set of variables that are in conflict with L_f in Γ . The costs of L_f and $L_x \in \Omega_f$ are recalculated for Γ' . If the new cost of L_x is zero, it means the lightpath assigned to L_x is no longer in conflict with the other lightpaths in Γ' ; thus, L_x is deleted from the CRL. If the cost of L_f is zero, L_f is deleted and the next variable in the CRL becomes the new *head*; otherwise, it means L_f must be in conflict with one or more variables in Γ' . Let Ω'_f

represents that set of variables. If a $L_y \in \Omega'_f$ is already in the CRL, L_y is moved to the head of the CRL. Other variables in Ω'_f are inserted into the head of the CRL one by one in a random sequence. With this method, the *head* L_f is renewed for each iteration, and the search process is guided to a new neighborhood based on the new *head*.

- 5) In order to prevent the TS from searching a recently searched neighborhood, a *tabu list* is used to store the recently searched CRL head L_f . We apply the *tabu rule* (TR) whereby, a Γ' , which may lead to a new CRL *head* that is forbidden by the *tabu list*, is marked with a tabu tag. A tagged solution is then dropped from the neighborhood $N(\Gamma)$ and no longer eligible to be selected as the next current solution.
- 6) An *aspiration rule* (AR) is applied to overrule the *tabu rule* when a good solution is found. For each iteration, if the cost of a tagged solution is better than the best cost achieved among all the iterations so far, the tabu tag is removed by this rule.
- 7) The TS subroutine stops based on two conditions. The first stoppage condition is when $C(\Gamma) = 0$, in this case, a *feasible solution* is found. The second condition is when the best cost achieved does not improve for $|\Delta|$ number of iterations. In this case, the TS subroutine is deemed to have failed in finding a *feasible solution*.

The pseudo codes of the proposed TS algorithm are as follow:

```

Begin of Main // Main TS algorithm
Construct the initial  $W$  with first fit algorithm;
While (TbSub( $W$ )=feasible) do {  $|W| := |W| - 1$ ; }
Return  $|W| + 1$ ;
End Of Main

TbSub( $W$ ) Subroutine //Begin of Subroutine
Construct initial solution  $\Gamma_{ini}$  ;
Create the CRL from  $\Gamma_{ini}$  ;
 $\Gamma := \Gamma_{ini}$ ; Cycle:=0;
While ( $C(\Gamma) \neq 0$  & Cycle  $\neq |\Delta|$ ) do
  Begin
     $L_f := \text{head of the CRL}$ ;
    Construct  $N(\Gamma)$  based on  $L_f$ ;
    Apply TR & AR to find the best  $C(\Gamma')$  for all  $\Gamma' \in N(\Gamma)$ ;
     $\Gamma := \Gamma'$ ; Update the CRL, the tabu list and Cycle;
  End of while
  If ( $C(\Gamma) = 0$ ) return feasible;
  Else return infeasible;
End of Subroutine

```

III. SIMULATIONS

Due to the stochastic nature of the TS algorithm, the construction of Γ_{ini} may lead to significantly different results. To evaluate the stability of our proposed algorithm, the following simulation is run. The test network is a large network with 50 nodes and 164 unidirectional links [7]. The lightpath requests set Δ is randomly generated with at most one request for each node pair. Two request sets with $|\Delta|$ equal to 300 and 500 are tested respectively. Ten executions for each test set are run with different random seeds. The cardinality of pre-calculated *candidate path set* (CPS) is set to 3, and tabu list tenure is set to $|\Delta|/3$. Table 1 shows the average, maximum, minimum number of wavelengths used for the ten executions. For the

TABLE I
RESULTS FOR 10 TRIALS

	Ave.	Max.	Min.	Std. Dev./Ave.
$ \Delta =500$	44.6	45	43	1.6%
$ \Delta =300$	28.8	29	28	1.5%

$|\Delta|=500$ set, the maximum result gap for different executions is 2 wavelengths, while the corresponding value for $|\Delta|=300$ set is 1. The standard deviations of the results for the 300 and 500 sets are about 1.5% and 1.6% of the average value respectively. This shows that our proposed algorithm exhibits reasonable performance stability.

The performance of the proposed TS algorithm is compared with the ILP solution proposed in [2]. Similar to our TS algorithm, the ILP solution is based on the pre-calculated CPS to provide the route for a request. When the pre-calculated CPS covers all the possible routes for a given request, the ILP solution is guaranteed to find an optimal result for the MWU problem. Since the ILP solution is guaranteed to obtain the best result among any CPS based algorithms, instead of comparing our algorithm with those CPS based algorithms in [1], [3], [4], we use the results obtained by the ILP solution as the benchmark to evaluate the effectiveness of our proposed TS algorithm. The first set of simulations is run for NSFNet [8], which has 14 nodes and 42 unidirectional links. The $|\Delta|$ varies from 84 to 168 with a step increase of 14. Ten request sets are generated for each $|\Delta|$. In total, 60 different Δ 's are tested. For a request in Δ , the same CPS is used in both TS algorithm and ILP solution, and covers all the possible routes for that request. In this case, the result obtained by the ILP is the optimum for the MWU problem. For each test set, the TS algorithm is run five times independently and the best result is chosen. The ILP formulation is solved using ILP problem solver CPLEX 8.1. For the 60 request sets tested, the proposed TS algorithm achieves the same result as the ILP solution. The same results are achieved for 60 request sets for another small network Cost239 [8] with 11 nodes and 52 unidirectional links. These results are clear indication of the capability of our proposed TS algorithm in finding optimum solutions for MWU problems of small networks.

Another set of simulation is run for a large network [7]. The $|\Delta|$ varies from 200 to 500 with a step increase of 100. Ten request sets are generated for each $|\Delta|$. In total, 40 different Δ 's are tested. To manage the computational time requirement, we limit the cardinality of CPS to 3 so that the ILP solution can be solved within reasonable time on our desktop computer with 2.4G CPU and 1Gbytes memory. The results show that for all the tested Δ 's with $|\Delta|=200, 300$ and 400, our TS algorithm achieves the same result as the ILP solutions. Only one out of the 10 tested Δ 's ($|\Delta|=500$) shows the TS algorithm obtaining an inferior outcome (see Fig. 1a). The difference is one wavelength with TS yielding 43 wavelengths and ILP yielding 42 wavelengths used. The average time for the ILP formulation with $|\Delta|=500$ is about 29 hours, while the TS algorithm can solve the problem within half an hour (see Fig. 1b). There are two reasons why the TS algorithm is able to achieve significant time saving. When the route and wavelength assignment are considered simultaneously, the size

Fig. 1. Result for 10 trials with $|\Delta|=500$: (a) number of wavelengths used; (b) running time.

of the solution search space is $|\Delta|^{W \times P_1}$ (we assume all the CPSs are of the same cardinality). To solve such a problem using the ILP, the entire solution space needs to be examined in order to guarantee an optimal result, hence time consuming. In our TS algorithm, the search process is guided by the CRL, a mechanism which enables the search to direct its focus from one localized sub-region (of cardinality $|W| \times |P_1|$) to another. With each iteration, the algorithm searches within the localized neighborhood to determine the fittest value. This leads to faster convergence to an optimal or near optimal solution without having to search the whole solution space.

IV. CONCLUSION

In this letter, we propose a TS algorithm to solve the well-known MWU problem. To the best of our knowledge, our approach is unique in the sense that our TS algorithm considers both routing and wavelength assignment jointly to achieve high quality results, while keeping computational cost low. The simulation results confirm that the TS algorithm can achieve superior performance for both small and large networks.

REFERENCES

- [1] D. Banerjee and B. Mukherjee, "A practical approach for routing and wavelength assignment in large wavelength-routed optical networks," *IEEE J. Select. Areas Commun.*, vol. 14, pp. 903-908, June 1996.
- [2] K. Lee and K. Choe, "Routing and wavelength assignment in WDM all-optical networks," *IEEE Electron. Lett.*, vol. 36, pp. 964-966, May 2000.
- [3] N. Banerjee and S. Sharan, "A evolutionary algorithm for solving the single objective static routing and wavelength assignment problem in WDM networks," in *Proc. IEEE ISIP'04*, Jan. 2004, pp. 13-18.
- [4] J. Kuri, N. Puech, M. Gagnaire, E. Dotaro, and R. Douville, "Routing and wavelength assignment of scheduled lightpath demands," *IEEE J. Select. Areas Commun.*, vol. 21, pp. 1231-1240, Oct. 2003.
- [5] F. Glover and M. Laguna, *Tabu Search*. Kluwer Academic Publishers, 1997.
- [6] J. Y. Yen, "Finding the K shortest loopless paths in a network," *Management Science*, vol. 17, pp. 712-716, July 1971.
- [7] S. Ohta and A. Greca, "Comparison of routing and wavelength assignment algorithms for optical networks," in *Proc. IEEE Workshop on High Performance Switching and Routing*, May 2001, pp. 146-149.
- [8] Y. Wang, T. H. Cheng, and B. Mukherjee, "Dynamic routing and wavelength assignment scheme for protection against node failure," in *Proc. IEEE GLOBECOM 2003*, Dec. 2003, pp. 2585-2589.