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Joint Routing and GCL Scheduling Algorithm Based on Tabu Search in TSN

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***Abstract*—Time sensitive networking (TSN) has been widely adopted and applied in many fields. The scheduling problem of TSN requires that the gate control list (GCL) is calculated according to the flow information in a given topology network. Conventional flow scheduling schemes are usually based on the given routing scheme, which limits the scheduling performance. Besides, current works mostly focus on the time trigger flows (TT). However, AVB flows exist as aperiodic flows in the industrial Internet. The integrated scheduling of these two types of flows is required to improve the overall schedulability. In this paper, a problem model of joint routing and GCL scheduling is proposed. An algorithm based on Tabu search (Tabu-RG) is proposed to solve the problem with specific design of neighborhood movement policy, neighborhood selection policy, as well as diversified function. Experimental results show that compared with the solver method, the proposed algorithm can save 75% of the time cost on the premise of ensuring the solution performance.**

***Keywords*—Time Sensitive Networking (TSN), Flow Schedule, Tabu Search (TS), Routing Schedule**

I. INTRODUCTION

In recent years, as a new generation of Ethernet technology, TSN has been widely adopted in various fields such as industrial Internet, avionics network, vehicle-mounted network, professional audio and video. TSN has received continuous attention from both academia and industry.

Flow scheduling is the core mechanism in TSN. Flow scheduling determines the transmission sequence and time of each data frame in all switch outbound ports through a certain scheduling algorithm. Through the proper flow scheduling, different types of service flow can coexist in the network. However, there are still some issues in current flow scheduling.

Firstly, the existing flow scheduling work is mostly based on the given routing scheme [1], [2], which is usually determined by the spanning tree algorithm or the shortest path routing algorithm. The pre-set routing mechanism only takes into account the routing-related metrics such as path length and load balancing, and does not consider the classification and performance requirements of each individual flow. Therefore, the latency performance of a flow may be affected.

Secondly, there are both TT flows and AVB flows in network. Most of the current works only focus on the scheduling of TT flows [3], [4]. However, under the condition of limited network resources, the scheduling of AVB flow will obviously affect the TT flow.

Besides, current methods mostly use solver to work out the flow scheduling scheme [6], [7]. However, such method has the problem of high computational complexity especially in the large-scale flow scheduling scenarios.

Regarding the aforementioned issues, in this paper, a tabu search algorithm for routing and GCL scheduling is proposed for both TT and AVB flow in time-sensitive networks. The main contributions of this paper are as follows: 1) A problem model of joint routing and GCL scheduling is proposed. 2) An algorithm for routing and GCL scheduling based on Tabu search (Tabu-RG) is proposed. 3) A scheduling policy for differentiated service flow is proposed, aiming at three types of Ethernet flow, which improves the efficiency of traffic scheduling in practical applications.

II. RELATED WORK

In this section, we review relevant studies from joint routing and GCL scheduling and methods for scheduling solution.

A. *Joint routing and GCL scheduling*

A lot of flow scheduling work is based on the given routing scheme, aiming at maximizing bandwidth utilization or minimizing total transmission time [2], [8]. Different from the above literatures, Atallah A et al. [8] explored the multi-path routing space by means of greedy randomized adaptive search procedures (GRASP) algorithm, obtained the route and grouping scheme with the least conflicts through multiple iterations and improved the scheduling performance.

In this paper, we propose an integrated routing and GCL scheduling problem model, which greatly expands the size of the solution space.

Besides, current researches [3], [4] mainly focus on the scheduling of TT flows, does not consider the influence of AVB flows on TT flows in real network environment. However, AVB flows do exist in the industrial Internet. To tackle this problem, Raagaard M L et al. [5] designed a scheduling mechanism based on GRASP, which aims to improve the schedulability of both TT and AVB flows, and uses the schedulability of AVB flows as the objective function to determine the quality of feasible solutions.

In this paper, we propose a scheduling mechanism based on Tabu Search to achieve simultaneous scheduling of TT and AVB flows.

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B. *Scheduling solution method*

Raagaard M et al. [5] proposed a TSN flow scheduling mechanism based on ILP. However, the solving time is exponential with the number of variables. Li Qing et al. [6] used SMT to calculate the time window allocation satisfying scheduling constraints, and then formed a scheduling scheme. However, these two methods take a long time to solve scheduling problems in large-scale networks.

Gavrilut V et al. [11] proposed a joint mechanism for flow scheduling based on TS. Compared to previous methods, TS has certain advantages in solving speed and the scalability of the network that can be solved.

In this paper, we utilize tabu search to plan the routing and schedule the GCL for TSN traffic, aiming to enhance scheduling flexibility and accelerate the solving speed.

III. PROBLEM MODEL

In this section, we present the system model and mathematical formulation of the joint routing and GCL scheduling problem.

A. *Network model*

The network is abstracted as directed graph $G(V,E)$. V is the set of node, including the network switch (NS) and end system (ES). $E \subseteq V \times V$ is the set of edges in which each element represents a one-way link. Each one-way link $[v_a, v_b]$ is defined by the triplet$< c_{ab}, d_{ab}, n_{ab} >$, the elements of which respectively represent the bandwidth capacity, propagation delay, and number of connected outgoing port queues of the link.

B. *Flow model*

The flow in TSN includes TT flow (HTS flow, LTS flow) and AVB flow. TT flow is used in real-time applications with strict time constraints and requires deterministic low delay guarantee. Among them, HTS flow is with short delay and LTS flow with long delay. AVB flow is used for soft real-time applications, providing bounded worst-case end-to-end delay, but with looser delay constraints than TT flow.

TT flow: A TT data flow $s_{Ti} \in S_T$ can be defined as a quad| $< D_{Ti}, J_{Ti}, C_{Ti}, T_{Ti} >$, the elements of which respectively represent the maximum end-to-end delay, the maximum jitter, data volume and period length of flow i.

AVB flow: An AVB data flow $s_{Ai} \in S_A$ can be defined as a triplet $< D_{Ai}, J_{Ai}, C_{Ai} >$, representing the maximum end-to-end delay, maximum delay jitter, and total amount of data that the flow can tolerate, respectively.

C. *Scheduling constraints*

To guarantee sequential and conflict-free transmission of frames in the network, the following scheduling constraints must be satisfied.

1) Frame constraints: (1) and (2) ensures that $\varphi_i^{[v_a,v_b]}$ be non-negative, and that the transmission of $S_i^{[v_a,v_b]}$ must be completed within its period.

$$\forall s_i^{[v_a,v_b]} \in S^{[v_a,v_b]}, [v_a,v_b] \in R_i, \varphi_i^{[v_a,v_b]} \geq 0 \tag{1}$$

$$\varphi_i^{[v_a,v_b]} \leq T_i^{[v_a,v_b]} - I_i^{[v_a,v_b]} \tag{2}$$

2) Link constraints: (3) and (4) are conflict-free transmission constraints, which ensure that any two data frames passing through the same link do not overlap in time.

$$\forall [v_a,v_b] \in E, s_i^{[v_a,v_b]} \in S^{[v_a,v_b]}, s_j^{[v_a,v_b]} \in S^{[v_a,v_b]}, i \neq j$$

$$\varphi_i^{[v_a,v_b]} + \alpha T_i^{[v_a,v_b]} \geq \varphi_j^{[v_a,v_b]} + \beta T_j^{[v_a,v_b]} + I_j^{[v_a,v_b]} \tag{3}$$

$$\varphi_j^{[v_a,v_b]} + \beta T_i^{[v_a,v_b]} \geq \varphi_i^{[v_a,v_b]} + \alpha T_i^{[v_a,v_b]} + I_i^{[v_a,v_b]} \tag{4}$$

α and β are integers, $\alpha \in [0, h_{ij}/T_i - 1], \beta \in [0, h_{ij}/T_j - 1], h_{ij}$ is the least common multiple of T_i and T_j.

3) Flow transmission constraint: (5) specifies the timing of a frame through each link on the path.

$$\forall s_i \in S, [v_a,v_x], [v_x,v_b] \in R_i$$

$$S_i^{[v_a,v_x]} \in S^{[v_a,v_x]}, s_i^{[v_x,v_b]} \in S^{[v_x,v_b]}$$

$$\varphi_i^{[v_x,v_b]} \geq \varphi_i^{[v_a,v_x]} + I_i^{[v_a,v_x]} + d^{[v_a,v_x]} + p_a + \delta \tag{5}$$

$d\,[v_a, v_x]$is the propagation delay of link $[v_a, v_x]$, p_a is the processing delay of node v_a, and δ is the maximum value of clock deviation in the whole network.

4) Delay constraints: (7) is the end-to-end delay constraint of real-time flow.

$$\forall s_i, R_i = [[v_1,v_2], \cdots, [v_{n-1},v_n]] \tag{6}$$

$$\varphi_i^{[v_{n-1},v_n]} + I_i^{[v_{n-1},v_n]} + d^{[v_{n-1},v_n]} - \varphi_i^{[v_1,v_2]} \leq L_i \tag{7}$$

The end-to-end delay must be less than or equal to the maximum end-to-end delay L_i that a flow can tolerate.

5) Jitter constraint: (11)is the jitter constraint for real-time flow.

$$\forall s_{Ti} \in S_T, s_{Ti} =< D_{Ti}, J_{Ti}, C_{Ti}, T_{Ti} > \tag{8}$$

$$R_i = [[v_1,v_2], \cdots, [v_{n-1},v_n]] \tag{9}$$

$$\tau_i = \sum_{k=1}^{n-1} I_i^{[V_k,V_{k+1}]} + \sum_{k=1}^{n-2} d^{[V_k,V_{k+1}]} + P_k \tag{10}$$

Where τ_i is the total transmission, propagation and processing delay of the frame from the end to end.

$$\varphi_i^{[v_{n-1},v_n]} - \varphi_i^{[v_1,v_2]} - \tau_i - W_i \leq J_i \tag{11}$$

$\omega_i^{[v_a,v_b]}$represents the ideal waiting time of the flow s_i on the link $[v_a, v_b]$, that is, the difference between the earliest transmission time and the arrival time without jitter.$W_i = \sum_{k=2}^{n-1} w_i^{[v_k,v_{k+1}]}$ represents the total ideal waiting time from the sending end to the receiving end.

6) Frame isolation constraint: The frame isolation constraint is defined in (12) ,(13) and (14).

$$\forall\,[v_a,v_b]\in E, s^{[v_a,v_b]}\in S^{[v_a,v_b]}, s^{[v_a,v_b]}\in S^{[v_a,v_b]}, i\neq j$$

$$\varphi_i^{[v_a,v_b]}+\alpha T_i+\delta\leq\varphi_j^{[v_y,v_a]}+\beta T_j+d^{[v_y,v_a]}+p_a \quad (12)$$

$$\varphi_j^{[v_a,v_b]}+\alpha T_j+\delta\leq\varphi_i^{[v_x,v_a]}+\beta T_i+d^{[v_x,v_a]}+p_a \quad (13)$$

$$P_i^{[v_a,v_b]}\neq P_j^{[v_a,v_b]} \quad (14)$$

Where $[v_x,v_a],[v_y,v_a]$ is any two predecessor links of the link$[V_a,V_b]$. For any two flows in the same queue, only when all the frames of one flow leave the queue, the frames of the other flow can start to queue.

D. Problem Formulation

The goal of the problem is to improve the schedulability of all types of flow in TSN network. The overall cost function is defined in (15).

$$cost=\sum w_i\cdot\delta_I \quad (15)$$

Where $\delta_i$is the schedulability of a single flow, and is defined in (16).

$$\delta_i=\begin{cases} c_i=\sum_i max\left(0,\varphi_i^{[v_{n-1}v_n]}+d^{[v_{n-1}v_n]}-D_i\right), \\ \quad if\ \exists\ \varphi_i^{[v_{n-1}v_n]}+d^{[v_{n-1}v_n]}>D_i \\ \sum_i(\varphi_i^{[v_{n-2}v_n]}+d^{[v_{n-1}v_n]}-D_i), \\ \quad if\ c_1=0 \end{cases} \quad (16)$$

$$W_i=1+[(\varphi_i^{[v_{n-1},v_n]}+d^{[v_{n-1},v_n]})\Big/_{D_i}]^{100} \quad (17)$$

When a flow is schedulable, the weight W_i is close to 1. Once a flow is unschedulable, the weight becomes extremely large, affecting the overall cost function. When the cost function is positive, it indicates that there are still some flows can not be scheduled. When it is negative or 0, it indicates that the delay is smaller than the service request, demonstrating the superiority of the scheduling scheme.

In order to achieve the optimization goal of minimizing the total cost of the network, the objective function of the joint routing and GCL scheduling problem is defined as (18).

$$\underset{\delta_i}{min}\ cost=\sum w_i\cdot\delta_i \quad (18)$$

IV. ALGORITHM DESIGN

The optimization problem proposed in section III.D is an NP complete problem [9], [10]. Compared with SMT/OMT, Tabu search has certain advantages in solving speed and the scalability of the network. The solution speed and the scale of the solvable network have certain advantages. Therefore, tabu search is adopted in this paper for scheduling solution.

A. Joint routing and GCL scheduling algorithm based on tabu search

In this section, the joint routing and GCL scheduling algorithm based on tabu search (Tabu-RG) is proposed, the steps of which are presented in Alg. 1.

Firstly, the network topology, the latency requirements and the flow set are input. The Prim algorithm is used to calculate the minimum spanning tree according to the requirements of each flow, and a random path is selected as the initial path. The scheduling order is based on the ASAP (As Soon As Possible) strategy, and the flows are scheduled in ascending order of their respective flow labels. We use S0 to calculate initial Best and Current solutions (line 1 to line2).

Both the cost function value and the number of iterations are used to set the termination conditions for the algorithm (line 3). First, we obtain the optimal cost function value and the number of iterations at convergence by running the algorithm for a long time [12]. We then set Setting.Cost to be 90% of the optimal cost function value and Times to be 110% of the number of iterations at convergence. The loop continues as long as the current cost function value is greater than Setting.Cost and the number of iterations is less than Times. If either of these conditions is not met, the algorithm terminates.

In each iteration, the tabu list is updated. A candidate solution set is generated by neighborhood movement strategy. Then, a candidate list obtained through neighborhood selection (line 4 to line 9). Next, the tabu list is updated based on the optimal solution of this iteration(line 10 to line 19). All the cost function value of solutions in the candidate list are calculated and the solution with the lowest cost function value is recorded.

If the generated neighborhood solution is better than the BEST(The optimal solution discovered so far), it is selected as the new BEST and Current (the current solution being searched). And it will then be put into the tabu list. If it is better than the Current and does not exist in the tabu list, it is selected as the new Current. And it will then be put into the tabu list. Finally, if the counter exceeds the set value, the diversification function is executed (lines 19-23). To implement both routing and GCL scheduling through tabu search, we design the neighborhood movement policy, the neighborhood selection policy, and the diversified function are designed, which will be elaborated subsequently.

B. Neighborhood movement policy

Neighborhood movement policy provides a candidate solution set for neighborhood selection (line 7), which is mainly divided into two parts: routing neighborhood movement and scheduling neighborhood movement. Routing neighborhood enables flows to choose different paths for scheduling, thus expanding the solution space. The scheduling neighborhood movement is to obtain the neighborhood solution set by controlling the time when the flow leaves the node.

The specific process is as follows: 1) Find out the range of delay or advance at each node. 2) After random selection within the above range, calculate whether the transmission

Algorithm 1: Simulation-optimization heuristic

```
Input: Network topology G, Flow set M, latency
       requirements T, Initial schedule $S_o$
Output: Corresponding scheduling of optimal
        solutions $S_{best}$
1  $\mathrm{S} \leftarrow \mathrm{So}, \mathrm{empty\ L}, \mathrm{counter} \leftarrow 0, \mathrm{times} \leftarrow 0$;
2  $General\mathrm{Best}, \mathrm{Current}\ (\mathrm{Best} = \mathrm{Current})\ according\ to\ the\ S^0$;
3  while $Cost(S) > Setting.Cost\ and\ times\ < Setting.Times$ do
4      $\mathrm{counter} \leftarrow \mathrm{counter} + 1, \mathrm{times} \leftarrow \mathrm{times} + 1$;
5      if $\mathrm{Size(L) = maxLSize}$ then
6          delete L.last;
7      end
8      Generate Candidate set according to neighbor movement
9      Generate Candidate list according to neighbor selection
10     $\mathrm{Next} \leftarrow solution$ from Candidate list that
         minimizes the cost function;
11     if $\mathrm{Cost(Next) < Cost(Best)}$ then
12         $\mathrm{Current} \leftarrow \mathrm{Next}, \mathrm{Best} \leftarrow \mathrm{Current}, \mathrm{S} \leftarrow \mathrm{Best}$;
13         $\mathrm{add\ tabu(Next)\ to\ L}$;
14     end
15     if $\mathrm{Cost(Next) < Cost(Current)}\ and$
         $\mathrm{tabu(Next){+}L}$ then
16         $\mathrm{Current} \leftarrow \mathrm{Next}, \mathrm{S} \leftarrow \mathrm{Current}$;
17         $\mathrm{add\ tabu(Next)\ to\ L}$;
18     end
19     if $counter > Setting.Counter$ then
20         $\mathrm{counter} \leftarrow 0$;
21         $\mathrm{Current} \leftarrow \mathrm{Diversity(Current)}$;
22         $\mathrm{empty\ L}$;
23     end
24     Return $\mathrm{S}^{\mathrm{best}}$
25 end
```

failure of other flows will be caused. If the new scheduling is feasible, it is the solution of the proposed scheduling neighborhood movement; otherwise, it will not be added.

C. Neighborhood selection policy

The generation of the neighbor solutions in tabu search facilities the search for schedulable solution. However, since the neighbor number of each solution is very large, it is infeasible to calculate all the neighbor solutions. Therefore, only a subset of candidate solution set called a candidate list can be calculated. In order to obtain the neighbor with better results, we designed a candidate list generation method(line 8). To generate a candidate list, We process HTS flows, LTS flows, and AVB flows according to different priorities. There are two situations where the scheduability of the flows will be affected: frames of an flow may not arrive because another flow arrives too early or an flow consumes too many resources, thereby preventing the current flow from utilizing them. For the former, reschedule the flows with the longest scheduling allowance on the link. For the latter, reschedule the maximum flow on the link. We first process unschedulable HTS flows. If the aforementioned two methods do not work, then sequentially apply them to LTS flows and AVB flows.

V. EXPERIMENTAL ANALYSIS

In this section, we evaluate the performance of our proposed joint routing and GCL scheduling algorithm based on tabu search (Tabu-RG).

A. Experimental environment

All simulations were run on a MacOs system with 2 GHz Intel Core I5 and 16GRAM. The proposed Tabu-RG is implemented and run in Python 2.7.

The configuration of 9 topologies and their flow settings are described in Table I . All links in the above topologies have a bandwidth of 100 Mbps. The data flows includes HTS, LTS and AVB. The DDL range of each kind of flow as well as the range of frame length are described in Table II.

The proportion of HTS, LTS, and AVB data flows depends on the requirements of the corresponding devices and services. The default ratio of three data flows in this paper is set as 2:2:6. To verify the effect of different flow ratios on the scheduling results, we also evaluate the performance of algorithms with five flow ratios in Table III under a middle-scale topology 4.

TABLE I: The configuration of 9 topologies and their flow settings

Topo No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
ES	4	8	12	20	30	50	70	100	31
NS	3	4	5	6	7	10	12	15	15
Flow	20	25	25	30	40	50	60	80	30

TABLE II: DDL and frame length

	H_DDL (ms)	**L_DDL (ms)**	**A_DDL (ms)**	**Frame (Byte)**
Max	2	10	2	30
Min	10	25	25	1500

B. Metrics and Comparison Method

We compare the performance of Tabu-RG with other algorithms on the following metrics.

1) metrics: The following metrics are used to evaluate the performance of the proposed approach.

- Scheduling success rate (%): The rate of the number of successfully scheduled flow sets that meet delay requirements to the total number of flow sets.

TABLE III: The flow ratio setting

No.	**1**	**2**	**3**	**4**	**5**
HTS	1	2	3	4	5
LTS	1	2	3	4	5
AVB	8	6	4	2	0

- Optimal cost function value (unit): Cost function value of the convergent solution.
- Solution time (s): The time consumed by the SMT-Z3 algorithm to obtain a successful scheduling solution.
- Convergence time (s): The time consumed by the Tabu-RG algorithm to obtain the convergent solution.

2) Comparison Method: In this paper, we evaluate the performance of the proposed algorithm Tabu-RG by comparing it with four algorithms: SS(Straightforward Solution), the solver method based on SMT-Z3, tabu search based routing schedule algorithm (Tabu-R), and tabu search based GCL scheduling algorithm (Tabu-G).

C. Simulation Results and Analysis

This section shows the simulation results and analyzes the performance of Tabu-RG algorithm.

1) Scheduling success rate: Fig. 1 show that the scheduling success rate of the first three algorithms is influenced by different topologies, flow settings, and flow ratios. The SMT-Z3 algorithm and Tabu-RG algorithm achieve a 100% success rate under all conditions. SMT-Z3 obtains the global optimal solution using a solver, while Tabu-RG achieves good search results through various strategies. The scheduling success rate of Tabu-RG is higher than that of Tabu-R and Tabu-G. The superiority of joint routing and GCL scheduling is verified.

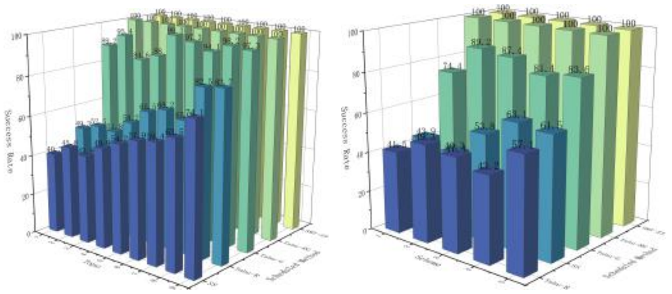
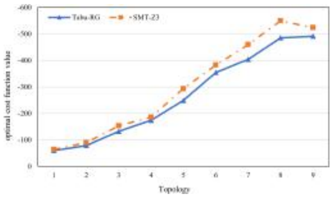


Fig. 1: Success rates of various algorithms. (a) Different topologies and flow settings. (b) Different flow ratio settings.



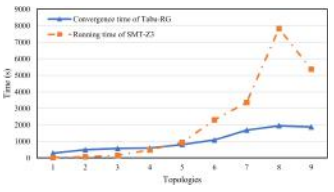


Fig. 2: Comparison of optimal cost function value under different topologies and flow settings.

Fig. 3: Comparison of convergence time of Tabu-RG and running time of SMT-Z3.

2) Optimal cost function value: We compared the cost function values of Tabu-RG and SMT-Z3. The results are shown in Fig. 2. In different settings, both algorithms can meet the delay requirements. The cost function value of Tabu-RG algorithm is slightly higher than that of solver method SMT-Z3. With the increase of topology and flow scale, the cost function value of Tabu-RG decreases continuously, which indicates that the proposed Tabu-RG can better meet the delay requirements in larger topology and flow conditions.

3) Execution efficiency : As shown the Fig. 3 the Tabu-RG algorithm proposed in this paper speeds up the solving speed of large topology and flow input. When the number of nodes reaches 115(topology 8), the proposed algorithm saves nearly 75% of the time cost compared with the solver.

VI. CONCLUSION

In this paper, we study flow scheduling in time-sensitive networks from the perspective of routing planning. A problem model of joint routing and GCL scheduling is proposed. A joint routing and GCL scheduling algorithm based on tabu search (Tabu-RG) is proposed to solve the problem. A mixed scheduling method of HTS, LTS and AVB is also designed to improve the overall schedulability and performance. Experimental results show that compared with the solver method, the proposed algorithm can save 75% of the time cost on the premise of ensuring the solution performance.

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