Communications Satellite Multi-Satellite Multi-Task Scheduling

H. J. Li\textsuperscript{a}\textsuperscript{*}, Y. Lu\textsuperscript{b}, F. H. Dong\textsuperscript{a}, R. Liu\textsuperscript{c}

\textsuperscript{a} PLA University of Science and Technology Institute of Communications Engineering, Nanjing 210007, China
\textsuperscript{b} Guangdong Provincial Military Region Command, Guangzhou 510501, China
\textsuperscript{c} Institute of China Electronic System Engineering, Beijing 100141, China

Abstract

Through research in task scheduling of related field domestic and overseas, this paper analyzes communication satellite tasks constraints based on task scheduling characteristics, such as communication tasks, satellite resources, time window constraints etc. The multi-satellite multi-task scheduling optimization model is established on the basis of dynamic constraint satisfaction problem (DCSP), meanwhile we build objective function and mathematic model. This paper develops a modified local change algorithm for the scheduling model. Compared with greedy algorithms and constraint propagation model by examples, the effectiveness of the proposed scheduling model was proved.

© 2011 Published by Elsevier Ltd. Selection and/or peer-review under responsibility of Harbin University of Science and Technology Open access under CC BY-NC-ND license.

Keywords: communication satellite; task scheduling; dynamic constraint satisfaction; local change algorithm.

1. Introduction

At present, the task scheduling researches focus mainly on earth remote sensing satellites, reconnaissance satellites. Such as area target of dynamic decomposition, with the aid of the rules of the heuristic algorithm based on dynamic realized and mitigation of the satellite task scheduling\cite{1}; The scheduling model on the basis of constraint satisfaction problem (CSP)\cite{2}, adopting the method of greedy algorithm and constraint propagation combined to complete remote sensing satellite multi-satellite multi-station task scheduling\cite{3}; Introducing to retain the selection mechanism, an improved hybrid genetic annealing algorithm solves the electronic reconnaissance satellites task scheduling problem\cite{4}, etc. However, task scheduling for communication satellites is still at the initial stage. Scheduling model in existing studies are mostly based on static SCP, it’s difficult to use static CSP model to solve the dynamic

*Corresponding author: H. J. Li; Tel: 18001150595; fax: 010-.
E-mail address: xclhj1985@163.com.
problem of communication satellite resources with tasks changing over time. When problem changes, CSP will reconsider the whole issue as a new problem, this solution is very time-consuming.

Here, we propose a dynamic constraint satisfaction problem (DCSP) [5] applied to the multi-satellite multi-task scheduling model. According to satellite communications features, this paper analyzes the communication tasks, communication resources, time windows and other major constraints, and establishes a multi-satellite multi-task scheduling optimization model based on dynamic constraint satisfaction problem. We also design a modified local change algorithm [6] for the scheduling model, the goal of the proposed task scheduling algorithm is to minimize resources consumption and maximize the weight of task priorities that can be scheduled.

2. Multi-satellite multi-task scheduling constraint analysis

Communication satellite task scheduling is an optimization problem based on constrained dynamic [7]: the limited resources are allocated to varieties tasks, and the goal is to complete as many tasks with priority. That means if there are available resources in the satellites, we should select maximum weights of the task priorities, with the fewest resources consumed. The key of model for satellite scheduling problem lies in how to select constraints. This paper is based on task scheduling problem constraints, resource constraints, time window constraints, etc.

2.1 Task constraints

Communications tasks is set as that: m = \{ m_j \mid 0 \leq j \leq N \} (N is dynamic).

(1) The basic characteristics elements of communication task: task bandwidth demands, task power needs, task time requirements, the service types of task need, task priority. The tasks constitution can be described by the set M as the following: M = \{ m_j \mid m_j = (B_j, P_j, T_j, O_j, U_j) \}.

There: M is a collection consisting of all the communication tasks; m_j represents communications task; B_j for task bandwidth demand; P_j for task power need; T_j for task time requirement; O_j for the service type of task; U_j for the priority of task. (O = \{ o_1, o_2, o_3, o_4, o_5 \}, set O on behalf of service types, o_1, o_2, o_3, o_4, o_5 represent voice services, video services, photo services, fax services, text services.)

(2) Task decomposition and clustering

Decomposition and clustering for all types of complex tasks are on basis of the demand characteristics analysis, and in the principle that all tasks are decomposed into subtasks occupying single executable resources; These tasks can be combined to get the executable assorts task sequence together through analyzing the relationship among task constraints(Fig 1). For the task m_j with the completion by multiple satellites, we need to decompose the task to form element composition of the subtask sequence. Task m_j may need various service types O_j, such as O_j1 that the voice services demand for task m_j, the bandwidth B_j and power requirements P_j are different for different service, and the service types are changing.

(3) The division of priority

As the satellite resources are limited and the demands of services are various, the importances of different tasks are not equal, so there existing constraints of task priorities. Priority determines the importance of the task. Lower priority tasks have to give way to the higher priority tasks in the condition that limited resources make priority to be the most important basis for task scheduling.

We assign a priority to each type of user, the tasks are given the same priority according to the user types, the priority of the task set is U = \{ u_1, u_2, \ldots, u_i, \ldots \}, and satisfies u_1 > u_2 > \ldots > u_i > \ldots, the priority U_j of task m_j can be any value of set U, so task scheduling must be based on the task priorities.

(4) Whether the task must be scheduled for execution
We define the decision variables \( w = \{ w_1, w_2, \ldots, w_j, \ldots \} \):

\[
w_j = \begin{cases} 
1. & \text{The task } m_j \text{ is scheduled for execution} \\
0. & \text{The task } m_j \text{ is not scheduled for execution}
\end{cases}
\]

\[
C_i = \begin{cases} 
w_n = 1 & \wedge j \in (N_n) \\
\wedge (w_j = 1) & \text{remaining tasks which can be scheduled for execution or not,}
\end{cases}
\]

Suppose that task \( m_j \) must be performed by \( C_p \), and \( C_i \) can be expressed as above. There \( w_n = 1 \) means that any subset of this task must be scheduled for execution, the national mission requirements and urgent tasks are included; \( \wedge j \in (N_n) (w_j = 1) \) means remaining tasks which can be scheduled for execution or not, mainly determined by the task’s priority and available resources of communication satellites.

### 2.2 Resource constraints

Assuming there are \( K \) communication satellites \( S = \{ S_1, S_2, \ldots, S_K \} \), available resources on the satellites mainly include satellite transponders, bandwidth, power, and support for different service types.

Satellite resources can be expressed by set \( \Psi \), resources of satellite \( S_k \): \( \Psi(S_k) = \{ S_{kA}, S_{kB}, S_{kP}, S_{kO} \} \).

\( S_{kA} \) represents the transponder resources of satellite \( S_k \); \( S_{kA} = \{ S_{kA1}, S_{kA2}, \ldots, S_{kAL}, \ldots \} \) expresses there are multiple available transponders on \( S_k \); \( S_{kB} \) for the bandwidth resources of \( S_k \); \( S_{kP} \) for the power resources of \( S_k \); \( S_{kO} \) for service types of \( S_k \), \( S_{kO} = \{ S_{kO1}, S_{kO2}, S_{kO3}, S_{kO4}, S_{kO5} \} \). \( S_{kO1}, S_{kO2}, S_{kO3}, S_{kO4}, S_{kO5} \) represents \( S_k \) supporting voice services, video services, photo services, fax services, and text services.

If the satellite \( S_k \) can establish at least a communication link, then \( S_k \) is said available to user terminal, otherwise unavailable. In a period the \( A_{ij} \) is recorded as whether the satellite \( S_k \) is available to task \( m_j \), we define the resource constraints as \( C_r \), representing the satellite resources selectivity and available Constraints. \( w_j = 1 \) indicates that the task is scheduled, \( w_j = 0 \) indicates that the task has not been scheduled.

\[
A_{ij} = \begin{cases} 
1. & \text{Express the satellite } S_k \text{ is available for the task } m_j \\
0. & \text{Express the satellite } S_k \text{ is not available for the task } m_j
\end{cases}
\]

\[
C_r(m_j) = \begin{cases} 
w_j = 0 & \\
w_j = 1 & (\sum A_{ij} \geq 1)
\end{cases}
\]

### 2.3 Time constraints

Multi-satellite multi-task scheduling problem not only means to schedule on the satellite resources, but also planning on the available satellite time window, so the available time window can be considered as a virtual resource. Scheduling problem of multi-satellite time window constraints includes task scheduling time constraints \( C_{time} \) and available satellite time window constraints \( C_w \). Scheduling time constraints: \( C_{time}(t) \rightarrow 0 \leq t_{js} < t_{je} \leq t_h \). Assuming the start time of task scheduling \( m_i \) is 0, the deadline is \( t_h \); start time is \( t_{js} \), end time is \( t_{je} \), the constraint means any given task must be completed before deadline. We define a time window needs variable \( Q_{jk} \), which means the task \( m_j \) requirement of satellite transponder. \( C_w \) is the time window for the demand constraints. Task \( m_j \) is scheduled then \( w_i = 1 \), or \( w_i = 0 \) expresses task \( m_j \) is not scheduled. The task \( m_i \) is assigned a time window at least one time slot if it is scheduled.

\[
C_w(m_j) = \begin{cases} 
w_j = 1 & (\cup Q_{jk} = \phi)
\end{cases}
\]

### 3. Multi-satellite multi-task scheduling model based on DCSP

#### 3.1 Dynamic constraint satisfaction problems

Dynamic constraint satisfaction problem is constituted of a series of static constraint satisfaction problems on a sequence in the Timeline. S. Mittal and B. Falkenhiner departed from the logic relation of
the variables, according to different activities of activation problems between relationships, the problem of different activities based on the relationship among the DCSP problem activations are described [6], Ari Kjönnson and Jeremy D. Frank departed from the strengthening and weakening of the constraint problem to illustrate the DCSP as a sequence of constraint satisfaction problems [8], as shown in Figure 2. It is defined as: Let $G = <V, D, C>$ as the CSP, then $G' = <V', D', C'>$ where $V$ is the set of variables, $D$ is the set range of variables, $C$ is a collection of constraint relations.

$V \supseteq V, \forall v \in V, D, \subseteq D, C \subseteq C, V'$ is called the enhanced CSP problem;

$V \supseteq V, \forall v \in V, D, \supseteq D, C \supseteq C, V'$ is called the weakening of the CSP problem.

3.2 Scheduling based on dynamic constraint satisfaction model

As the tasks, resources, constraints are dynamic over time, therefore, multi-satellite multi-task scheduling problem can be expressed by set $G: G = <M(t), S(t), T_w, C(t)>$. There, $M(t)$ is the set of tasks representing the communication task set waiting for scheduling with dynamic time; $S(t)$ is the set of resources on the satellite payload, representing all the resources on the satellite in running; $T_w$ is the time window set; $C(t)$ for the set of constraints related that change over time, mainly including the task constraints, resource constraints and time window constraints.

If $G = <M(t), S(t), T_w, C(t)>$ expresses multi-satellite multi-task scheduling problem, then the main constraints of the problem is the task constraints ($C_t$), resource constraints ($C_r$), and time window constraints ($C_{time}, C_w$): $C(t) = C_t \land C_r \land C_{time} \land C_w$.

On dynamic constraint satisfaction problems, according to the variable convention, constraint analysis and the objective function, the paper establishes multi-satellite multi-task scheduling optimization model. Multi-satellite multi-objective function optimization task is to complete the task priority weighting function, meanwhile, try to minimum the satellite resources occupied by scheduling tasks in premise to complete the task.

$$\max \sum_{0 \leq j \leq N} W_j U_j \quad \min \sum_{0 \leq j \leq N} W_j B_j \quad \min \sum_{0 \leq j \leq N} W_j P_j \quad W_j = \{0, 1\} \quad \min \sum_{0 \leq j \leq N} W_j P_j$$

$$\sum_{0 \leq j \leq N} W_j B_j < \sum_{0 \leq k \leq K} S_{dk} \quad \sum_{0 \leq j \leq N} W_j P_j < \sum_{0 \leq k \leq K} S_{kp} \quad O_{j \leq k \leq N} \leq \sum_{0 \leq k \leq K} S_{kp} \quad C_{time}(m_j) \rightarrow 0 \leq t_j < t_e \leq t_h$$

$$C_t = \begin{cases} w_n = 1 & \text{if } j \in \{N-n\} \\ w_n = 1 & \text{if } j \in \{N-n\} \end{cases}$$

$$C_{cl}(m_j) = \begin{cases} w_j = 0 & \text{if } \sum A_{kj} \geq 1 \\ w_j = 1 & \text{if } \sum A_{kj} \geq 1 \end{cases}$$

$$C_w(m_j) = \begin{cases} w_j = 0 & \text{if } \cup Q_{jk} \neq \emptyset \\ w_j = 1 & \text{if } \cup Q_{jk} \neq \emptyset \end{cases}$$
4. Model solution based on the modified local change algorithm

Steps for solving the problem of dynamic constraint satisfaction mainly as following [8]:

(1) Describe the Constraint problem, clear and definite key elements, variables, variables’ domain and constraints of constraint problem.

(2) Establish scheduling model based on the dynamic constraint satisfaction problems.

(3) Get the solution of initial time \( t = 0 \) by the static CSP solution.

(4) Solve the model on the basis of variables, variable’s domain and the change of constraint condition when problems change with time.

Local change algorithm is an efficient algorithm in solving reuse technology [7]. Its main idea was to start from the initial solution of previous proceeding, adjust the variables of those conflict domains in the changed issues, until the variables assigned values be able to meet all the problem constraints. Local change algorithm makes the former problems solution information in full use in the next solving process, avoiding repeatedly computation by re-solving. Therefore, local change algorithm is very suitable for application in highly real time requirement of satellite communication task scheduling.

In the communication task scheduling process, three types of dynamic changes are often encounter: argument changes (such as task \( M(t) \) is added or finished), argument domain changes (communication satellite resources \( S(t) \) adjustments) and other constraints \( C(t) \) changes (including the time window \( T_w \)). Contraposing three major dynamic changes in task scheduling processes, this paper designs a modified local change scheduling algorithm to solve the model. The principle is: we adjust the assignment of conflicting arguments, that is in scheduling time \( t_j \) owing to the task will engender changes in the implementation of the new variables (new communication tasks) or delete existing variables (the original communication tasks were finished), or constraints change in time \( t_j \) (increase or decrease the constraints). The above makes some arguments in previous time \( t_i \) conflicting with some constraints in time \( t_j \), which requires re-assignment for the argument; In the process of assignment or re-assignment for argument, if the new assignment are in conflict with existing constraints, the assignment for argument requires to be repaired, after that, which also lead the assignment to conflict with other variables, then we need to continue to generate conflict till engender a set of assignment meet all the constraints in scheduling time \( t_j \).

5. Example Analysis

According to the communication task scheduling model and the corresponding solution based on dynamic satisfaction above, we set a communication task scheduling as an example for practical application analysis of the previously designed scheduling model.

The hypothesis period is 15 Mar 6:00:00-17 Mar 18:00:00, in an area 1.5 million square kilometers of land within the users' sudden communication tasks scheduling planning. According to the level of tasks priority and the different scheduling periods, tasks are divided into six task sets \( m' \) by decomposition and clustering, each task set contains a certain number of sub-tasks implemented by a satellite's single resources. Obviously, the requirements of different task set for service types, power and bandwidth are different. There are three available communication satellites, the availability of each satellite for tasks is different, \( A_{kj} = 1 \) indicates several satellites are available for the task \( m_j \). Task scheduling resources are as shown in Table 1.

Adopting the model based on greedy algorithm and constraint conditions spread [9] respectively to solve the match problem between communication satellite resources and task, we obtained three satellites to guarantee tasks for the entire area was 65.18%. Through the object oriented model language UML programming solution to scheduling model, in accordance with the task scheduling resources in table 1 on the constraint conditions of related, this paper utilize the modified local change algorithm to
choose the solution of the biggest objective function values as the optimal algorithm solution in the simulation. The average task completion rate reached 97.32% in 30 times simulation. The results comparison shows that the dynamic constraint-based scheduling model and solution algorithm satisfied the dynamic tasks requirements and effectively improved communications support for regional users.

Decomposition of the task set after sorts communication

<table>
<thead>
<tr>
<th>Service type</th>
<th>Task power</th>
<th>Task bandwidth</th>
<th>Subtasks number of Clustering</th>
<th>Predecessor task sets</th>
<th>Satellite resources requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>m_1</td>
<td>O_{12},O_{14}</td>
<td>P_1</td>
<td>B_1</td>
<td>N_1</td>
<td>m_2,m_3,m_6 A_{11} \cap A_{31} \cap A_{3} = 1</td>
</tr>
<tr>
<td>m_2</td>
<td>O_{21},O_{22},O_{23},O_{24},O_{25}</td>
<td>P_2</td>
<td>B_2</td>
<td>N_2</td>
<td>m_6 A_{12} \cap A_{22} = 1</td>
</tr>
<tr>
<td>m_3</td>
<td>O_{31},O_{32},O_{33}</td>
<td>P_3</td>
<td>B_3</td>
<td>N_1</td>
<td>NO A_{33} = 1</td>
</tr>
<tr>
<td>m_4</td>
<td>O_{42}</td>
<td>P_4</td>
<td>B_4</td>
<td>N_4</td>
<td>m_3 A_{44} \cap A_{34} = 1</td>
</tr>
<tr>
<td>m_5</td>
<td>O_{51},O_{52},O_{53},O_{54},O_{55}</td>
<td>P_5</td>
<td>B_5</td>
<td>N_5</td>
<td>m_5,m_6 A_{15} \cap A_{35} \cap A_{55} = 1</td>
</tr>
<tr>
<td>m_6</td>
<td>O_{61},O_{65}</td>
<td>P_6</td>
<td>B_6</td>
<td>N_6</td>
<td>m_4 A_{16} \cap A_{36} = 1</td>
</tr>
</tbody>
</table>

| Tab.1 Resource scheduling table |

6. Conclusion

Contraposing the task scheduling based on the communication satellite resources, this paper proposes an idea of scientific allocation of resources and the optimization scheduling tasks, and analyzes such communication tasks, communication resources and time window as the main constraint conditions. We establishes a multi-satellite multi-task scheduling optimization model on account of dynamic constraint satisfaction optimization problems, designing a modified local change algorithm to solve the scheduling model. Finally an example under the setting conditions verified the effectiveness of this scheduling mode, indicating that the constructed model and the algorithm is feasible. The paper will play a guiding role of theory in the scientific and rational use of communication satellite resources.

References


