Paper

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Genetic algorithm–based scheduling for ground support of multiple satellites and antennae considering operation modes

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Abstract

Given the unpredictability of the space environment, satellite communications are manually performed by exchanging tele-commands and telemetry. Ground support for orbiting satellites is given only during limited periods of ground antenna visibility, which can result in conflicts when multiple satellites are present. This problem can be regarded as a scheduling problem of allocating antenna support (task) to limited visibility (resource). To mitigate unforeseen errors and costs associated with manual scheduling and mission planning, we propose a novel method based on a genetic algorithm to solve the ground support problem of multiple satellites and antennae with visibility conflicts. Numerous scheduling parameters, including user priority, emergency, profit, contact interval, support time, remaining resource, are considered to provide maximum benefit to users and real applications. The modeling and formulae are developed in accordance with the characteristics of satellite communication. To validate the proposed algorithm, 20 satellites and 3 ground antennae in the Korean peninsula are assumed and modeled using the satellite tool kit (STK). The proposed algorithm is applied to two operation modes: (i) telemetry, tracking, and command and (ii) payload. The results of the present study show near-optimal scheduling in both operation modes and demonstrate the applicability of the proposed algorithm to actual mission control systems.

Key words: genetic algorithm, mission control system, ground support, visibility conflict, scheduling optimization, operation mode

1. Introduction

Communication between a satellite and a ground antenna is performed when the satellite passes through the ground antenna's "visibility"—i.e., the cone-shaped region of communication extending from the antenna. Satellites are controlled and operated using tele-commands and telemetry, which are transmitted and received within the radio visibility between ground antennae and satellites. Satellites are largely operated by manual commands owing to the unpredictability of the space environment. Satellite operational missions are largely divided into two modes: 1) telemetry, tracking, and command (TTC) for maintaining orbit, tracking satellites, and the state of health (SOH); 2) payload (PL) for undertaking the

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mission of the satellite and sending the acquired data via a downlink [1].

When two or more satellites simultaneously pass over a ground station, visibility conflicts occur because most ground antennae can only support one satellite at a time. As the number of satellites increases, the frequency of visibility conflicts increases; additionally, allocation of communication data within the visibility becomes problematic, and operational and mechanical considerations increase exponentially. Currently, mission control operations, including satellite–antenna scheduling, are performed manually [2-5]. However, manual scheduling generates unexpected errors and is inefficient.

The mission control system for the Korea Multi-Purpose Satellite (KOMPSAT) series was developed by the Korea Electronics and Telecommunications Research Institute (ETRI) and Korea Aerospace Research Institute (KARI) [6-8]. KOMPSATs are low Earth orbit (LEO) satellites following a sun-synchronous orbit of Korea; their main mission is acquiring images of Earth. Currently, KARI operates KOMPSAT 2, 3, 3A, and 5 with a very low frequency of visibility conflicts, because their orbital parameters are designed to avoid visibility conflicts. However, additional KOMPSATs will soon be introduced [9]. Hence, an algorithm is needed that can automatically solve ground support problems due to visibility conflicts.

1.1 Previous work

Scheduling optimization problems have mainly been studied in industrial engineering [10, 11]. Specifically, the ground support allocation problem is similar to assigning *N* jobs to *M* machines or a multiple-knapsack problem; the difference, however, lies in the fact that the visibility (resource) of one satellite can block that of others, and it exists for only a predetermined period before expiring [1, 12, 13]. Many studies have been performed on scheduling methods for satellite missions. KARI developed an automated algorithm for mission scheduling that focuses on a single satellite [14-16]. Dishan et al. [17] and Frank et al. [18] proposed dynamic and static scheduling methods for Earth observation (EO) satellites. However, they proposed heuristic methods for scheduling that do not guarantee the optimality of their solution. Lin et al. [19, 20] studied the daily image scheduling of a low-orbit EO satellite and solved a scheduling problem for single satellite operation.

The methodology of visibility conflicts has also been studied. Globus et al. [21, 22] applied various stochastic algorithms and made comparative analysis of the mission operation of EO satellites. ArKari et al. [23] tried to solve the conflict problem of satellite visibility via a deterministic approach, which is impractical. The Indian Space Research Organization (ISRO) devised a model using a genetic algorithm to solve conflicts between Indian Remote Sensing satellites (IRSs) [1, 24, 25]. Castaing [26] established visibility scheduling for multiple satellites and multiple ground control centers. ISRO and Castaing claimed that they used a genetic algorithm to solve the visibility conflict problem but did not present any detailed information about the methodologies, which means that their approach could not be reconstructed. Gwangju Institute of Science and Technology (GIST) and KARI presented a solution to the conflict problem of visibility using multi-antenna scheduling (MAS) [27] and a genetic algorithm [28]. Corrao et al. [29] proposed a resolution of the visibility conflict between multiple satellites and a single ground antenna by using a wide spectrum of algorithms. However, their research did not consider antenna support time and real operation modes. Xhafa et al. [30] and Spangelo et al. [31] studied the allocation of communication data within the visibility between multiple satellites or ground antennae and a single ground antenna or; a single satellite and multiple ground antennae, respectively. However, they did not consider multiple satellites and multiple ground antennae. Xhafa et al. [32, 33] developed an algorithm for numerous satellites and ground antennae using a genetic algorithm; however, operational factors were not acquired and verification was not performed for various operating modes.

1.2 Proposed model

In this study, we resolve the ground support problem during periods of visibility via a genetic algorithm for the KOMPSAT series. The algorithm provides maximum benefits to the user by taking into account various considerations in terms aspects of actual operation such as user priority, operational urgency, profit, contact interval, support time, satellite performance, and benefit. For the simulation, we assume multiple satellites with sun-synchronous orbits and multiple ground antennae with visibility conflicts, which are modeled using STK. The proposed algorithm is verified for the TTC and PL modes. We demonstrate that this algorithm can be applied to real operations.

The contributions of this paper are as follows. 1) We propose an algorithm for antenna support scheduling of multiple satellites and ground antennae. Unlike the majority of previous related papers, which merely considered mathematical modeling of scheduling, this paper has practical value because the proposed method can be applied to the real operations of the KOMPSAT series. 2) We design an optimization formula and a genetic algorithm for solving such a problem. Generally, the satellite-scheduling problem is regarded as an NP-hard problem [34-38]. In this case, a deterministic formula cannot be applied, and every possible scheduling should be searched. Therefore, we creatively design decision variables and a chromosome to apply a stochastic approach. 3) We account for scheduling considerations and operation modes in the proposed algorithm such that a near-global optimal scheduling result is obtained despite numerous scheduling parameters and mechanical constraints.

The rest of this paper is organized as follows. In Section 2, we introduce concepts related to visibility and associated conflicts. Section 3 defines the scheduling parameters. The modeling and formulation are presented in Section 4. In Section 5, a genetic algorithm is designed. Section 6 details the simulation conditions for applying the algorithm. In Section 7, results are presented and analyzed. Finally, we summarize and conclude our study in Section 8.

2. Background

2.1 Visibility

Figure 1(a) illustrates the visibility of a satellite and ground antenna. The start and end times of visibility are defined as the acquisition of signal (AOS) and loss of signal (LOS), respectively. The actual communication is executed by allocating communication data within the visibility while considering the transmission rate, as shown Fig. 1(b).

2.2 Visibility conflict

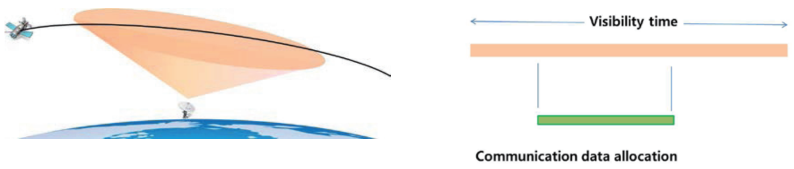
When two or more satellites simultaneously pass over a ground antenna or the AOS of a following satellite occurs before the LOS of the prior satellite, a visibility conflict occurs—i.e., each satellite blocks the visibility of the other satellite—as illustrated in Fig. 2. The visibility to which communication data is allocated should be selected according to the mission and operation mode. The difference between the last LOS and the first AOS is designated as the total visibility time (TVT).

2.3 Support and reconfiguration of antenna

Actual communication is executed through the support of the ground antenna within the visibility. Specifically, the ground antenna tracks the satellite moving along the orbit, and the line of sight of the antenna points to the satellite. When the antenna support transitions from one satellite to another, some reconfiguration time is required for mechanical movement or software initialization.

3. Scheduling considerations

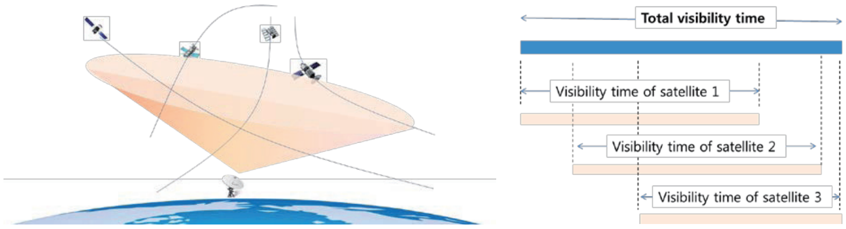
Satellites passing over ground antennae cannot communicate simultaneously in multiple-satellite operation. Consequently, satellites are selected for efficient communication such that no supporting conflict arises. The following seven conditions are taken into account in selecting satellites and ground antennae for communication.



(a) Visibility of satellite and ground antenna

(b) Data allocation during visibility

Fig. 1. Communication between satellite and ground



(a) Multiple satellites and a single ground antenna

(b) Total visibility time

Fig. 2. Visibility conflict of multiple satellites

3.1 User priority (W_1)

This parameter represents the priority that users determine arbitrarily. It represents the value of the requesting customer. Users can utilize this value to intervene in the scheduling algorithm in case of an unexpected situation.

3.2 Emergency (W_2)

This parameter is given in accordance with the level of urgency. The SOH of satellites is regularly monitored. Satellites with SOH-related urgency must have a larger weight than other satellites. A value of 100 is used in the control operation for at-risk satellites, and 0 is used for healthy satellites.

3.3 Profit (W_3)

Profit expresses the financial benefits of contacting the satellite. Among multiple satellites, a satellite that provides a higher profit is preferably selected. For an imaging mission, the profit is the price of the images acquired by the satellite.

3.4 Contact interval (W_4)

Larger weights are assigned to satellites that have been contacted less recently. Given that satellite SOH is monitored periodically, if a satellite does not make contact with the ground antenna for an extended period of time, its SOH cannot be checked, which affects mission planning. For example, if an imaging satellite does not make contact with the ground antenna for a long time, the image data will remain on the onboard memory and the satellite cannot execute its inherent mission. Hence, the satellite must be preferentially selected. Considerations for the contact interval are presented in Table 1.

Table 1. Weights of contact intervals

Contact interval	Weight
1–2 hours	5
3–4 hours	10
5–6 hours	15
7+ hours	20

3.5 Support time (W_5)

The required communication time for each satellite, i.e., the required support time (RST), should also be a consideration in satellite selection. A satellite with a long RST brings less benefit to the user. Therefore, such satellites should be given less preference in selection. The weight of support time is determined from the RST as

$$W_5 = \frac{1000}{RST} \tag{1}$$

3.6 Satellite performance (W_6)

This parameter represents the quality of payload data. In an imaging mission, a satellite with a higher-precision lens generates more sophisticated images; therefore, it is given a larger weight. Table 2 summarizes the performance weights.

3.7 Remaining resource (W_7)

The remaining resources of a satellite are also considered in satellite selection. A satellite consumes resources such as electric power and onboard memory to obtain ground images. Therefore, satellites with fewer remaining resources must be selected preferentially (i.e., given larger weights) to downlink their stored data. Table 3 gives the weights for remaining resources.

4. Problem description and formulation

We assume a situation with numerous satellites and ground antennae with visibility conflicts. The ground antennae are located close to each other, and each can support one satellite at a time. Support via the ground antennae is required for communication. The start and end of the RST are called the support start time (SST) and support end time (SET), respectively. An example of RST allocation for one ground antenna and three satellites is shown in Fig. 3. The RST of a satellite is allocated within the TVT. Reconfiguration time is required in order to support other satellites after allocation

Table 2. Weights of satellite performance

Satellite performance	Weights
High	45
Middle	30
Low	15

Table 3. Weights of remaining resources

Remaining resources	Weight
0–20%	30
20–40%	24
40–60%	18
60–80%	12
80–100%	6

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to the previous satellite. Communication among multiple satellites and a ground antenna can be converted to a task-scheduling problem by treating the RST and visibility as task and resource, respectively, to be allocated within the TVT.

4.1 Design variables and parameters

Design variables and parameters are obtained considering a chromosome in a genetic algorithm. The problem of scheduling multiple satellites and visibilities is regarded as an NP-hard problem. Accordingly, the designed formula is stochastic–deterministic. The overall variables are designed in an N × 3 array for N satellites:

$$\bar{\bar{X}} = [\text{Satellite index}_i, \text{Antenna index}_i, \mathrm{p_i}], \mathrm{p_i} \in \{0, 1\} \qquad (2)$$

The first and the second columns in the array contain design variables defined by the user, which represent communication. The third column represents parameters that depend on the design variables, and it plays the role of activating communication while considering constraints.

The satellite and antenna indices represent a sequential numbering for satellites and antennae. The subscript i indicates the row of the array. In the first column, the satellite index is randomly defined up to the number of satellites without overlap. In the second column, the antenna index is defined randomly. In the same row, the RST corresponding to the satellite is assigned to the visibility corresponding to the satellite and antenna index, which represents the communication between the satellite and antenna. The RSTs of satellites are allocated to the corresponding antennae sequentially from the first row to the last of the array. As allocation continues, visibilities, RSTs, and reconfigurations conflict with each other. If a conflict occurs, the communication is not executed and the parameter corresponding to the index is assigned as zero. Otherwise, the parameter corresponding to the executed index set is given as one. The design variable characterizes the order of the satellite index and the randomness of the antenna index. The parameter is determined according to whether the communication is performed. A scheduling example is explained in Section 5.1 with a chromosome.

4.2 Objective function

The optimization problem has the following objective function:

$$\text{maximize } f(\bar{\bar{X}}) = \sum_{i=1}^{N} S_i \times p_i \qquad (3)$$

where $S_i = \sum_{j=1}^{7} F_j w_j$, w is the weight of scheduling, F is the ratio that depends on the operation mode, p is an integer and is 0 or 1 for each satellite, and S_i is the summation of the product of weights and operation ratios corresponding to the satellite index$_i$. The objective function is expressed in a similar form as the 0-1 knapsack problem. RST and S_i correspond to the items and priority in the knapsack algorithm. However, the visibility in the TVT does not exactly correspond to the knapsack, which is the reason that the knapsack algorithm is not directly applied.

4.3 Constraints

The RST that corresponds to the satellite index of the design variables is allocated to the visibility corresponding to the satellite and antenna index. The RST must be within the visibility time:

$$AOS_i \le SST_i \le SET_i \le EOS_i \qquad (4)$$

The reconfiguration time is added to the RSTs of satellites allocated to each antenna's TVT, and the SET of the allocated RST must be smaller than the SST of the subsequent RST to be allocated:

$$SET_k + Reconfiguration\ time \le SST_{k+1} \qquad (5)$$

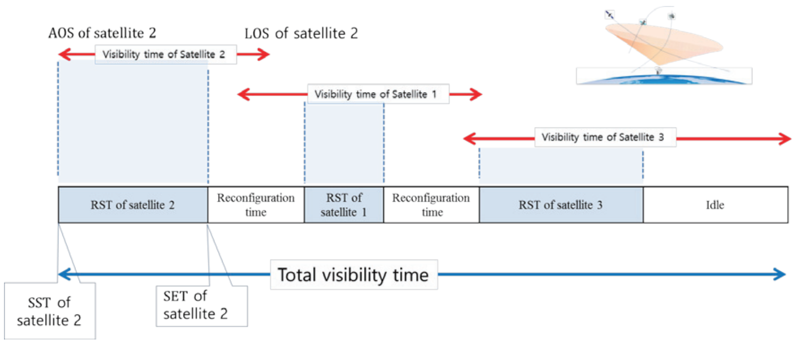


Fig. 3. Example of support time allocation

5. Genetic algorithm design

5.1 Chromosome design

The chromosome based on the design variables and the parameters described in Section 4.1 is composed of three terms: the satellite index, the antenna index, and the gene expression. The gene expression corresponds to the parameter. The diversity and feasibility of the chromosome are embodied through random generation of the index and the gene expression. The chromosome of an optimal TTC scheduling is shown in Fig. 4. The scheduling is performed sequentially with respect to the genetic expression marked as 1. Beginning from the far left edge of the chromosome, the RST of the 7th satellite is allocated to the visibility between the 7th satellite and the 2nd antenna. Although the allocation is continuously performed from left to right, it causes a resource conflict at the 13th satellite; thus, communication is not performed with the 13th satellite. The schema in the genetic algorithm is defined as the gene order in this algorithm.

5.2 Crossover and mutation

If a general crossover method is used, the same satellites will overlap. A satellite should exist without overlap to maintain diversity and feasibility within a chromosome. Therefore, a cycle crossover is applied and the gene expression term is recalculated sequentially. Examples of the crossover used in this study are shown in Fig. 5.

Mutation is selectively applied after the crossover depending on the initial mutation ratio. Two genes are randomly selected, and their order and the corresponding antenna are randomly changed. Then, the gene expression terms are also recalculated. The overall proposed algorithm is shown in Fig. 6. The concepts of the algorithm are based on the previous study [28] that focused on visibility allocation in the entire TVT for visibility conflict avoidance. In this study, enhanced optimal scheduling is conducted by allocating ground antenna support (actual communication time) to the visibility.

6. Simulation conditions

In this study, a ground support resolution algorithm for visibility conflicts is proposed based on KOMPSATs. However, the visibilities of currently operation KOMPSATs scarcely conflict with each other; therefore, the conflicts are not of sufficient complexity to require an optimization algorithm. However, because more satellites will be deployed in the future, we assume numerous sun-synchronous orbit satellites whose specifications are randomly generated analogous to the current KOMPSATs. Three terrestrial antennae are assumed according to Korean ground control stations. Visibilities between the satellites and ground antennae are calculated through the STK (Fig. 7). Fig. 8 shows the visibility between the 1st antenna and satellites

Satellite index	7	14	6	3	8	12	15	11	13	9	10	5	18	2	19	17	4	1	16	20
Antenna index	2	2	3	1	1	2	3	3	3	3	1	3	2	2	2	2	2	2	2	1
Genetic expression	1	1	1	1	1	1	1	1	0	0	1	1	1	0	0	0	0	0	0	0

Fig. 4. Chromosome in TTC optimal scheduling

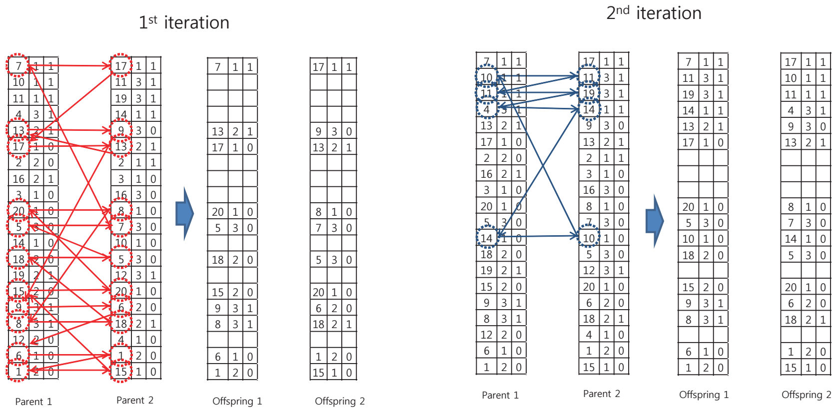


Fig. 5. Cycle crossover application

and the resulting conflicts during a 30 min simulation period from 04:00:00.000 to 04:30:00.000 UTCG on Feb 21, 2014. The satellites contacting the three ground antennae and generating visibility conflicts during the period are selected (Table 4).

6.1 Satellites

Twenty satellites are assumed for this simulation. The orbit information of the satellites and their scheduling considerations are summarized in Table 4. Sun-synchronous orbit satellites are assumed, and each has local time and altitude information. Their indices are numbered according to the AOS of the satellites. Based on the considerations described in Section 3, numerical values are given in sequence. Individual satellites require the support of ground antennae for the duration of their RST during the visibility.

6.2 Antennae

Three ground antennae are assumed. Their details are

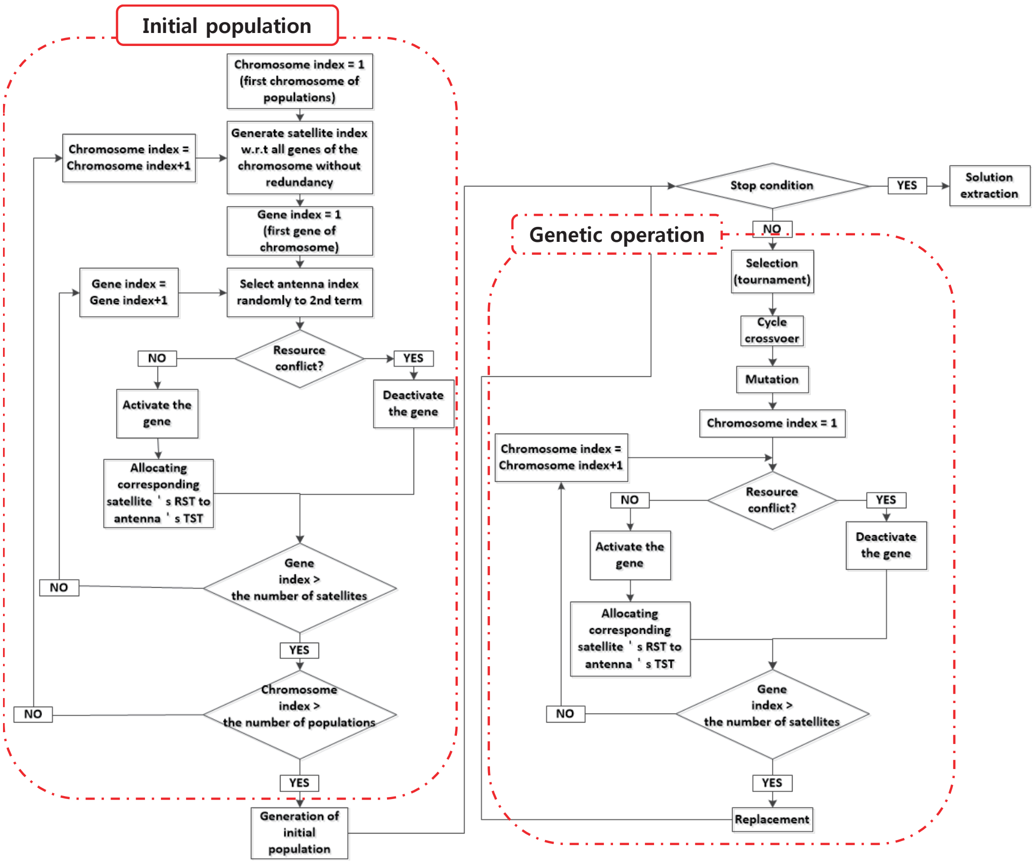


Fig. 6. Proposed genetic algorithm procedure

Fig. 7. STK modeling

given in Table 5, where the antenna index indicates the station number and latitude and longitude represent the position. As this study focuses on the Korean satellite environment, the ground antennae are assumed to be located in Seoul, Daejeon, and Goheung. The cone half-angles of all antennae are defined as 60°.

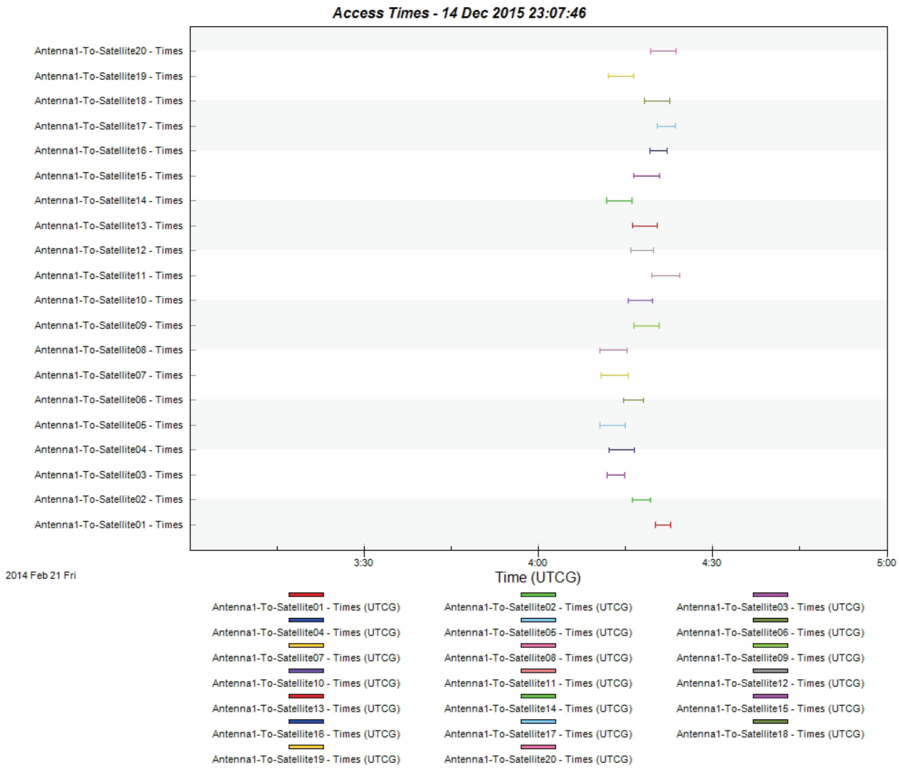


Fig. 8. Visibility between 1st antenna and satellites

Table 4. Scheduling considerations of satellites

Satellite index	Priority	Emerg ency	Profit	Contact interval (hours)	Satellite performance	Remaining resources (%)	RST (s)	Altitude	Local time (descending node)
1	5		30	2	High	8	114.3	698.7	11:41
2	2		40	1	Low	28	149.7	684.6	12:53
3	7		10	5	Low	52	157.6	673.2	11:43
4	9		30	3	High	65	158.0	675.6	12:03
5	6		40	8	Middle	25	128.6	670.6	12:13
6	4	100	20	10	Low	22	181.8	680.2	12:48
7	3		20	5	High	85	137.5	671.0	12:17
8	1		50	7	Low	82	151.1	699.9	12:29
9	3		20	2	Low	15	175.7	687.6	12:37
10	7		20	4	Low	45	169.8	684.2	12:38
11	8	100	30	6	Low	23	165.0	698.5	12:22
12	2		10	6	High	82	108.5	685.1	12:44
13	7		30	1	Low	84	159.5	686.8	12:41
14	8		40	7	Middle	23	101.5	673.0	12:30
15	4		30	2	Low	15	111.6	687.7	12:24
16	10		50	1	Middle	86	127.1	693.5	13:13
17	2		10	6	Low	55	109.2	697.5	12:58
18	2		30	7	Middle	12	179.2	693.3	12:19
19	1		40	5	Middle	61	171.9	674.1	12:31
20	6		50	1	Low	65	112.4	696.6	12:44

6.3 Visibility

The visibilities between the twenty satellites and the three ground antennae are listed in Table 6 and calculated with respect to corresponding satellites and antennae as the difference between the LOS and AOS, which causes a conflict between satellites. The TVT is expressed as the difference between the last LOS and the first AOS. The TVT is the period during which the antennae can provide support.

Table 5. Ground antenna positions

Antenna index	Latitude	Longitude	Cone half-angle
1	37.6° N	127.0° E	60°
2	36.4° N	127.4° E	60°
3	34.6° N	127.3° E	60°

6.4 Reconfiguration time

The reconfiguration time is assumed as 50 seconds. In terms of task scheduling, the reconfiguration time is allocated between the RSTs.

7. Results

7.1 Application to operation modes

The proposed algorithm is applied to two operation modes: TTC and PL. In the case of TTC, the emphasis is on telemetry and tele-command communication for maintaining the SOH of the satellites. The commands that have a large influence on SOH, such as urgency and contact interval, are given larger weights than other data. In the case of PL, the focus is on obtaining the inherent payload such as image data and its benefits; therefore, satellite performance and remaining

Table 6. Visibility between ground antennae and satellites

Antenna index	1			2			3		
Satellite index	AOS (mm:ss)	LOS (mm:ss)	Visibility (s)	AOS (mm:ss)	LOS (mm:ss)	Visibility (s)	AOS (mm:ss)	LOS (mm:ss)	Visibility (s)
1	20:04.4	22:49.1	164.7	20:40.8	22:46.5	125.7	21:28.3	22:53.2	85.0
2	16:13.2	19:23.8	190.5	16:24.0	19:50.9	206.8	16:49.8	20:21.9	212.1
3	11:49.2	14:49.4	180.2	12:21.2	14:51.3	150.1	13:01.8	15:04.8	123.0
4	12:12.6	16:34.2	261.6	12:34.3	16:47.6	253.3	13:04.8	17:11.9	247.1
5	10:37.0	14:59.8	262.8	10:58.3	15:13.6	255.3	11:28.4	15:38.2	249.8
6	14:36.3	18:07.3	211.0	14:48.5	18:32.7	224.3	15:14.5	19:03.3	228.8
7	10:49.2	15:24.6	275.4	11:07.5	15:42.3	274.8	11:35.6	16:09.5	273.8
8	20:03.6	24:49.3	285.7	20:21.3	25:07.8	286.4	20:49.3	25:35.5	286.1
9	16:24.9	20:49.2	264.3	16:40.4	21:10.6	270.1	17:07.4	21:39.7	272.3
10	15:23.8	19:41.6	257.7	15:38.9	20:03.4	264.5	16:05.8	20:32.8	267.0
11	19:32.0	24:17.5	285.5	19:50.9	24:34.4	283.4	20:19.6	25:01.1	281.5
12	15:53.8	19:52.9	239.2	16:07.6	20:16.5	248.8	16:34.1	20:46.4	252.3
13	16:18.0	20:30.3	252.4	16:32.7	20:52.8	260.2	16:59.4	21:22.4	263.0
14	11:42.0	16:05.8	263.8	11:57.9	16:26.5	268.6	12:25.0	16:55.3	270.3
15	16:21.7	20:52.4	270.7	16:37.8	21:13.0	275.2	17:05.0	21:41.8	276.8
16	19:12.1	22:10.7	178.6	19:22.0	22:39.0	197.0	19:47.6	23:10.4	202.8
17	20:23.0	23:33.2	190.3	20:33.6	24:00.7	207.1	20:59.4	24:31.9	212.6
18	18:14.2	22:40.3	266.1	18:29.7	23:01.7	272.0	18:56.7	23:30.8	274.1
19	12:04.1	16:27.0	262.9	12:19.9	16:47.8	268.0	12:46.9	17:16.7	269.8
20	19:25.1	23:41.6	256.6	19:39.8	24:04.1	264.3	20:06.6	24:33.7	267.1
First AOS (hh:mm:ss)			10:37.0			10:58.3			11:28.4
Last LOS (hh:mm:ss)			24:49.3			25:07.8			25:35.5
TVT (s)			852.3			849.5			847.1

Table 7. Ratio depending on the operation mode

Case	User priority	Emergency	Profit	Contact interval	Support time	Satellite performance	Remaining resources	Total
TTC	1	4	0.25	4	0.25	0.25	0.25	10
PL	1	0	3	0.25	0.5	3	2.25	10

resources received larger weights. The relative importance of the scheduling considerations is summarized in Table 7.

7.2 Simulation results

A simulation is executed for the modeling and the genetic algorithm presented in Section 5 and 6, respectively. The simulation conditions of the genetic algorithm are given in Table 8. The number of populations and generations are 100 and 500, respectively. The selection pressure of the roulette selection is set at 5. The two operation modes (TTC and PL)

Table 8. Simulation conditions

Hardware and simulation tools		Genetic condition	
Processor	Intel® Core™ i7-4790 CPU @ 3.60 GHz	Number of populations	100
Memory (RAM)	16 GB	Number of generations	500
Simulation tools	MATLAB 2011 a	Mutation ratio	5%
		Selection pressure	5

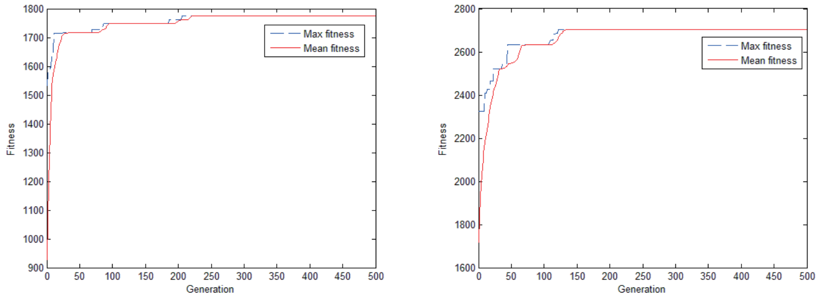
Table 9. Scheduling results and running time

(a) TTC mode

Satellite index	AOS	EOS	SST	SET	Objective
Antenna - 1					
3	11:49.2	14:49.4	11:49.2	14:26.8	80.0
10	15:23.8	19:41.6	15:23.8	18:13.6	62.4
8	20:03.6	24:49.3	20:03.6	22:34.7	101.1
				Sum	243.6
Antenna - 2					
Satellite index	AOS	EOS	SST	SET	Total objective
7	11:07.5	15:42.3	11:07.5	13:25.0	83.4
14	11:57.9	16:26.5	14:15.0	15:56.5	115.1
12	16:07.6	20:16.5	16:46.5	18:35.0	80.6
18	18:29.7	23:01.7	19:25.0	22:24.2	106.5
				Sum	385.6
Antenna - 3					
Satellite index	AOS	EOS	SST	SET	Total objective
5	11:28.4	15:38.2	11:28.4	13:37.0	112.3
6	15:14.5	19:03.3	15:14.5	18:16.3	500.7
15	17:05.0	21:41.8	19:06.3	20:58.0	46.0
11	20:19.6	25:01.1	21:48.0	24:33.0	487.4
				Sum	1146.5
Number of allocated satellites					11
Total objective					1775.6
Runtime (seconds)					55.1

(b) PL mode

Satellite index	AOS	EOS	SST	SET	Objective
Antenna - 1					
4	12:12.6	16:34.2	12:12.6	14:50.6	268.1
2	16:13.2	19:23.8	16:13.2	18:43.0	227.1
1	20:04.4	22:49.1	20:04.4	21:58.6	305.1
				Sum	800.3
Antenna - 2					
Satellite index	AOS	EOS	SST	SET	Total objective
19	12:19.9	16:47.8	12:19.9	15:11.8	246.0
12	16:07.6	20:16.5	16:07.6	17:56.1	190.9
15	16:37.8	21:13.0	18:46.2	20:37.8	214.2
20	19:39.8	24:04.1	21:27.8	23:20.2	235.7
				Sum	886.8
Antenna - 3					
Satellite index	AOS	EOS	SST	SET	Total objective
5	11:28.4	15:38.2	11:28.4	13:37.0	280.6
14	12:25.0	16:55.3	14:27.0	16:08.5	284.1
9	17:07.4	21:39.7	17:07.4	20:03.1	180.9
16	19:47.6	23:10.4	20:53.2	23:00.2	270.4
				Sum	1016.1
Number of allocated satellites					11
Total objective					2703.2
Runtime (seconds)					57.5



(a) TTC mode (a) PL mode

Fig. 9. Fitness variations according to generation

are analyzed separately, the results of which are summarized in Table 9. At-risk satellites, i.e., the 6th and the 11th are allocated in TTC mode, not PL mode. The 5th, 6th, 8th, 14th, and 18th satellites, which have not made contact for more than seven hours, are all allocated in TTC mode. The 1st, 9th, and 15th satellites, which have the fewest remaining resources, are allocated in PL mode. These patterns represent the effect of the operation mode (Table 7). Fig. 9 depicts the fitness, which characterizes the genetic algorithm, as the generations progress. The fitness result shows that the algorithm performed suitably in both operation modes. The simulation was conducted in MATLAB 2011a, and the hardware conditions are listed in Table 8. The computational runtime was approximately 50 s for both TTL and PL modes, which is reasonable for real applications (Table 9). The chromosome described in Fig. 4 is implemented as the scheduling type in Table 9.

8. Conclusion

We proposed a near-global optimal scheduling algorithm for ground support allocation of multiple satellites and ground antennae via a genetic algorithm, focusing on KOMPSATs. The proposed algorithm not only provides maximum benefit to the user but also enhances applicability to actual operations by considering various scheduling factors and operation modes. Because satellite–antenna scheduling is an NP-hard problem, an optimization formula and a genetic algorithm were specially designed. We designed decision variables and a chromosome as an array type to satisfy diversity, feasibility, and convergence. The algorithm was verified through simulation. The convergence and near-optimality are evident in fitness plots. By applying different relative weighting depending on the operation mode, i.e., TTC and PL, we showed that the proposed method is applicable to various operation modes using examples.

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