Contact Plan Design for Navigation Satellite Network Based on Simulated Annealing

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***Abstract*—By introducing inter-satellite links (ISLs), global navigation satellite system (GNSS) can achieve inter-satellite ranging, which can enable autonomous navigation, and inter-satellite communication, which can enable the GNSS to form a global network. Due to the resource constraints of satellite platforms, only limited number of ISLs (e.g. only one ISL) can be equipped on one navigation satellite, which makes the navigation satellite network a delay/disruption tolerant network (DTN). Generally, the number of ISLs is less than the number of visible satellites; thus, only those visible satellites which can together meet an overall goal shall be selected. Therefore, contact plan, which comprises all future contacts among satellites, needs to be carefully designed to accommodate the constraints of both inter-satellite ranging and inter-satellite communication. In this paper, a topology handling scheme based on finite state automaton is first presented as the orbiting of GNSS is periodic. Secondly, the contact plan design problem is formulated as a constraint optimization problem with the inter-satellite ranging as a constraint and inter-satellite communication delay as the optimization object. Thirdly, a heuristic algorithm based on simulated annealing is proposed to compute the contact plan. Simulation results show that the delay performance of optimized contact plan is improved and the delay of contact graph routing under optimized contact plan is also improved.**

Keywords—global navigation satellite system; contact plan design; constraint optimization; simulated annealing; communication delay; contact graph routing

I. Introduction

By introducing inter-satellite links (ISLs), global navigation satellite system (GNSS) can achieve inter-satellite ranging and inter-satellite communication[1]. Inter-satellite ranging can enable GNSS to implement autonomous navigation which can enhance the orbit and clock prediction accuracy and reduce dependence on ground infrastructure while Inter-satellite communication can enable GNSS to form a global network. GSP III plans to employ higher frequency directional ISLs to enable higher communication rate and higher anti-jamming capability [2].

Due to the resource constraints of satellite platforms, each navigation satellite can equip only limited number of ISLs (e.g. only one ISL), which makes the navigation satellite network a delay/disruption tolerant network (DTN) [3, 4]. Generally, the number of ISLs equipped on one navigation satellite is less than the number of visible satellites; thus, we shall only select those visible satellites which can together meet an overall goal, such as minimizing the network delay or maximizing the network fairness. Therefore, contact plan, which comprises all future contacts among satellites and used by contact graph routing (CGR) [5], designed particularly for interplanetary Internet, needs to be carefully designed to meet the requirements of both inter-satellite ranging and inter-satellite communication. The inter-satellite ranging requires the navigation satellite to establish more ISLs with more satellites to get more inter-satellite ranging measurements to enable higher precision of autonomous navigation [6] while the inter-satellite communication requires the navigation satellite to consider the time evolving nature of navigation satellite networks [7]. These two requirements could lead the contact plan design to different directions.

Currently, the contact plan design for GNSS has received little attention. Noakes et al [8] focused on contact plan that can enhance network connectivity through distributed optimization. Chang et al [9] proposed a finite state automaton (FSA) based link assignment which can minimize the maximum link utilization. However, the authors of [8, 9] all focused on contact plan design for communication satellite networks which don't need to consider the inter-satellite ranging requirement as well as the time evolving nature of the topology.

Huang et al [10] proposed topology control methods that can minimize path cost and maximize reliability in predictable DTN while Fraire et al focused on fair [7] and routing-aware [11] contact plan and proposed several contact plan design algorithms for predictable DTN. However, these works mainly focus on communication satellite networks or remote sensing satellite networks and don't need to consider the inter-satellite ranging requirement.

Shi et al [12] focused on contact plan that takes into account of both crosslink ranging and data exchange requirement of ISL in GNSS. However, the author of [12] don't need to consider the time evolving nature of the topology as each satellite can be equipped on three ISLs.

This paper focuses on the contact plan design of navigation satellite networks with limited number of ISLs (only one ISL can be equipped on one satellite) with the consideration of both inter-satellite ranging and inter-satellite communication requirement. Firstly, a topology handling scheme based on FSA is proposed and the contact plan design problem is formulated as a constraint optimization problem. A heuristic algorithm based on simulated annealing is proposed to solve the contact plan design problem. Simulation results show that the delay performance of

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optimized contact plan is improved and the delay of CGR under optimized contact plan is also improved.

The rest of this paper is organized as follows. Section II presents the topology handling scheme while section III formulate the contact plan design problem as a constraint optimization problem. Section IV proposed a contact plan design method based on simulated annealing and performance evaluation is presented in section V. We finally conclude the paper in section VI.

II. TOPOLOGY HANDLING

Two navigation satellites must be visible to set up ISL, therefore, in this part, we firstly formulate the visibility condition between two satellites and then present the topology handling scheme.

A. Visibility Between Satellites

Due to the earth shadowing and pointing limits of ISLs, not all navigation satellites can set up ISLs between each other. In this paper, we define two navigation satellites visible if they are not shadowed by the earth and the ISL antennas lie within the pointing region. The visibility of navigation satellites will evolve as the operation of GNSS constellation and exhibits a periodical feature.

Fig. 1 is the visibility geometry between navigation satellites and the earth, where R is the radius of the earth, h_s is the altitude of navigation satellite, d is the distance between two navigation satellites $S1$ and $S2$, h_a is the visibility margin to account for the effect of atmosphere, etc.

With the consideration of earth shadowing, two satellites are visible if their distance is less than a maximum, i.e. the following condition should be satisfied:

$$d < 2\sqrt{\left(R+h_s\right)^2-\left(R+h_a\right)^2}$$

Fig. 2 is the satellite visibility due to the pointing limits of ISLs, where the normal vector of ISL antenna points to the center O of the earth and the pointing region is a cone with a half angle θ.

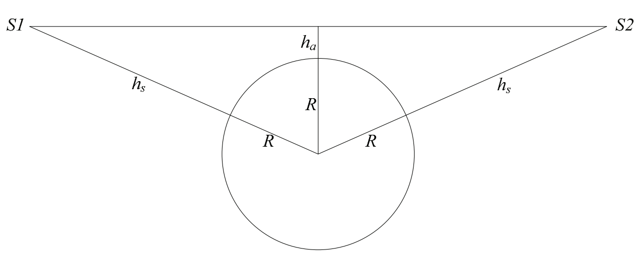


Figure 1 Visibility geometry between the earth and navigation satellites.

In Fig. 2(a), the ISL antennas are out of the pointing region, thus ISL cannot be set up between them. In Fig. 2(b), the ISL antennas are in the border of the pointing region and we assume ISL cannot be set up under this condition. In Fig. 2(c), the ISL antennas are within the pointing region, thus ISL can be set up between them. Therefore, with the consideration of ISL pointing limits, two satellites are visible if their distance is larger than a minimum, i.e. the following condition should be satisfied:

$$d > 2\left(R+h_s\right)\cos\theta$$

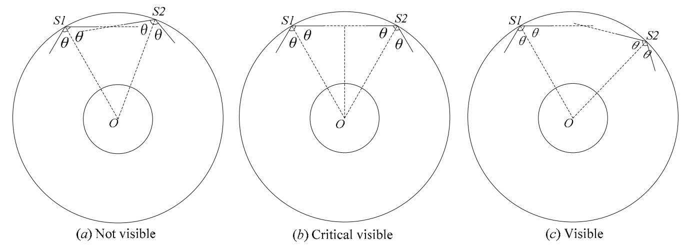


Figure 2 Visibility between satellites due to the pointing limits of ISLs.

In summary, two satellites are visible if their distance satisfies the following condition:

$$2\left(R+h_s\right)\cos\theta < d < 2\sqrt{\left(R+h_s\right)^2-\left(R+h_a\right)^2}$$

B. Topology Handling Based on FSA

Since the operation of navigation satellite constellation is periodic and motivated by finite state automaton [9], we divide the system period T of navigation satellite network into N equal-length time intervals and each time interval corresponds to an FSA state. Two satellites are said to be visible in an FSA state if and only if they are visible throughout the FSA state. The contact plan design is performed in each FSA state based on fixed visibility.

Inter-satellite ranging requires navigation satellites to complete more times of ranging in less time to increase the precision of autonomous navigation and the number of ISLs equipped on one satellite is less than the number of visible satellites, therefore, navigation satellites need to switch their ISLs to enable multiple inter-satellite ranging. In this paper, we further divide one FSA state into M equal-length time intervals and denote it as one contact plan period. Each contact plan period is then divided into K equal-length time slots. Fig. 3 shows the topology handling scheme, where cpp is the abbreviation of contact plan period. Navigation satellites will set up ISLs with different visible satellites in different time slots. The contact plan design is performed in each FSA state and all cpps in one FSA state will use the same contact plan generated in the corresponding FSA state.

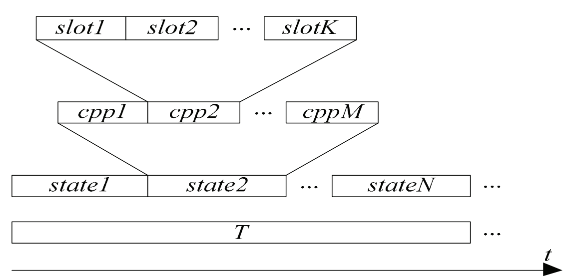


Figure 3 The topology handling scheme.

III. FORMULATION OF CONTACT PLAN DESIGN PROBLEM

The contact plan of navigation satellite network should satisfy requirements of both inter-satellite ranging and inter-satellite communication. We formulate contact plan design problem as a constraint optimization problem while inter-satellite ranging requirement is regarded as a constraint and inter-satellite communication delay is regarded as the optimization object.

Index:

$i, j = 1, 2, \cdots, S$, satellite,

$k = 1, 2, \cdots, K$, time slot,

Variable:

$v_{i,j}$ Visibility between satellite i and j within certain FSA state, V=[$v_{i,j}$] is visibility matrix

$u_{i,j,k}$ Connectivity between satellite i and j within time slot k, U=[$u_{i,j,k}$] is connectivity matrix which is also the contact plan

$c(i,j,k)$ Cost of the earliest delivery path between satellite i and j within time slot k

Objective function:

$$F = \frac{1}{K}\frac{1}{S(S-1)}\sum_{k=1}^{K}\sum_{i=1}^{S}\sum_{j=1, j\neq i}^{S} c(i,j,k)$$

Constraint:

$$v_{i,j} - u_{i,j,k} \geq 0, \forall i,j,k \quad (1)$$

$$\sum_{j=1}^{S} u_{i,j,k} = 1, \forall i,k \quad (2)$$

$$v_{i,j} = v_{j,i}, \forall i,j \quad (3)$$

$$u_{i,j,k} = u_{j,i,k}, \forall i,j,k \quad (4)$$

$$\sum_{k=1}^{K} u_{i,j,k} \leq 1, \forall i,j \quad (5)$$

$$v_{i,j} \in \{0,1\}, \forall i,j \quad (6)$$

$$u_{i,j,k} \in \{0,1\}, \forall i,j,k \quad (7)$$

$$K \geq 8 \quad (8)$$

We consider the average delay of navigation satellite network as the objective function and the average delay is calculated among all satellite pairs and all time slots (since the paths will be different in different time slots). The earliest delivery path is calculated by CGR.

(1) is the visibility constraint which means two satellites must be visible if they want to set up ISL. (2) is the constraint of maximum number of ISLs and we only consider one ISL equipped on one satellite and this only ISL must be set up. (3) and (4) are the symmetry constraints of visibility and connectivity matrix. (5) is the inter-satellite ranging constraint which means one satellite pair can set up ISL within only one time slot or don't set up ISL at all. (5) guarantees that one satellite will set up different ISLs with different visible satellites in different time slots to enable maximum number of inter-satellite ranging. (6) and (7) state that $v_{i,j}$ and $u_{i,j,k}$ can only take 0 or 1. (8) is the minimum number of time slots in a contact plan period.

IV. CONTACT PLAN DESIGN BASED ON SIMULATED ANNEALING

Since the contact plan problem formulated in last section will quickly become computationally intractable as the addition of nodes or time slots, we use a heuristic algorithm based on simulated annealing, which has been proved to be a good algorithmic approach in topology design problem [9, 11], to get sub-optimal solutions. Fig. 4 is the flow chart of contact plan design based on simulated annealing.

Firstly, we generate a random initial contact plan upon which we will generate a new contact plan. The new contact plan is generated based on branch and exchange [9, 11]. Then, the objective function of the new contact plan and the initial contact plan will be calculated and compared. If the objective function of the new contact plan is less or equal than that of the initial contact plan, we accept the new contact plan and decrease temperature T, or we accept the new contact plan with the following probability:

$$P = e^{-\Delta F/T}$$

where, ΔF is the objective function difference between new contact plan and old contact plan; T is a parameter that controls the process of simulated annealing. The probability of accept a worse contact plan is higher with higher T and the probability is lower with a lower T. rand(0,1) can generate a random number between 0 and 1. The temperature T will decrease according to the following rule as the iteration progresses to enable the iteration to terminate at a steady state:

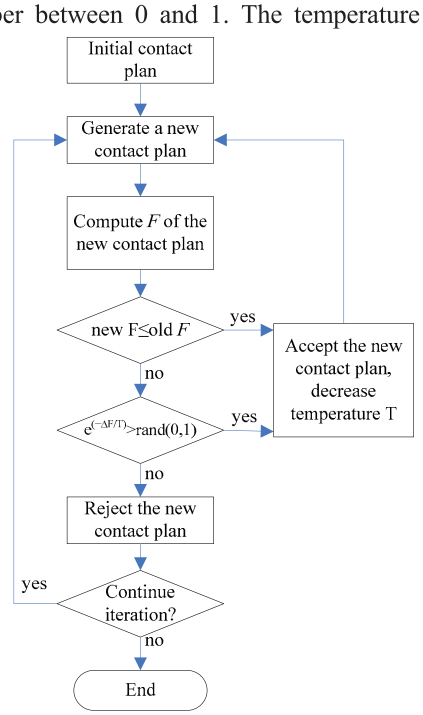


Figure 4 The flow chart of contact plan design based on simulated annealing.

$$T_{new} = \beta T_{old}, 0 < \beta < 1$$

where, β is the decreasing rate of the temperature T. The iteration will continue until maximum iteration has been met.

V. PERFORMANCE EVALUATION

A. Topology Handling Results

We evaluate the performance of contact plan design based on simulated annealing in a typical navigation satellite constellation which is walker-δ 24/3/2. There are totally 24 satellites in 3 orbits and the phase offset of the corresponding satellites in adjacent orbits is 360°/24*2=30°. The altitude of the constellation is 20232 km while the inclination is 55°. Each navigation satellite can only equip one ISL and the pointing limit of the ISL is [−60°, 60°], i.e. θ=60°.

The topology handling results are shown in Table I. There are totally 72 FSA states in one system period and each FSA state contains 25 contact plan periods. The duration of one time slot is 3 s and there are totally 8 time slots in a contact plan period.

TABLE I. PARAMETERS OF TOPOLOGY HANDLING BASED ON FSA

Parameter	Value
System Period (T)	720 min
Number of FSA states (N)	72
FSA state duration	10 min
Number of link assignment periods (M)	25
Link assignment period duration	24 s
Number of time slots (K)	8
Time slot duration	3 s

Since the number of visible satellites in each FSA state must be larger than the required number (8 as K=8) of inter-satellite ranging, we calculate the number of visible satellites in each FSA state for each satellite and the visibility margin is set to h_a=20 km. Fig. 5 is the number of visible satellites of the first satellite in each orbit. It can be seen from Fig. 5 that all three satellites have 15~17 visible satellites in each FSA state. We have verified that all satellites have no less than 15 visible satellites in each FSA state which satisfies the minimum number of inter-satellite ranging requirement.

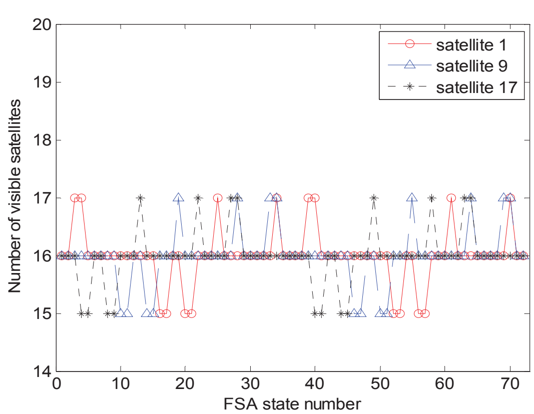
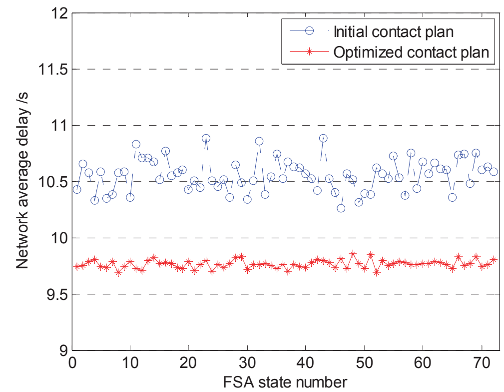


Figure 5 The number of visible satellites of the first satellite in each orbit in all FSA states.

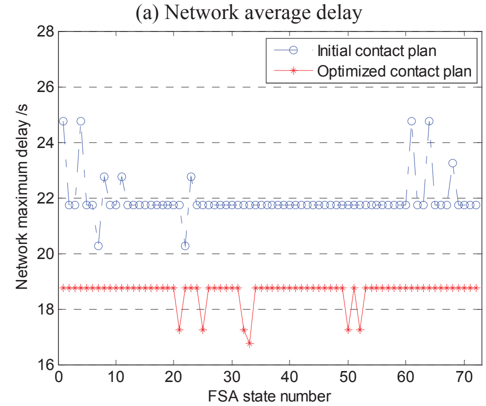
B. Contact Plan Design Results

The initial value and the decreasing rate of temperature T are set to 10 and β=0.95, while the maximum iteration number is set to 5000. Fig. 6 is the delay comparison between initial contact plan and optimized contact plan obtained through simulated annealing. It can be seen from Fig. 6(a) and Fig. 6(b) that both the network average delay and maximum delay are improved through all FSA states.

Table II is the statistical delay comparison between initial and optimized contact plan. The mean and standard deviation of network average delay are improved by 7.50% and 74.86%, respectively while the mean and standard deviation of network maximum delay are improved by 15.13% and 43.09%, respectively.



(a) Network average delay



(b) Network maximum delay

Figure 6 Delay comparison between initial and optimized contact plan.

TABLE II. STATISTICAL DELAY COMPARISON BETWEEN INITIAL AND OPTIMIZED CONTACT PLAN

		Initial	Optimized	Improvement ratio
Network average delay	mean	10.56	9.76	7.50%
	standard deviation	0.14	0.04	74.86%
Network maximum delay	mean	21.94	18.62	15.13%
	standard deviation	0.78	0.44	43.09%

C. OPNET Simulation Results

We conduct a simulation in OPNET to evaluate the delay performance of CGR under initial and optimized contact plan. The ISL rate is set to 50 kbps and message size is set to 2048 bits. Messages are generated in each satellite and the destination of the message is a random satellite. The inter-arrival time of the message generation is constant.

We first set the message inter-arrival time to 0.5 s and the cumulative distribution function (CDF) of CGR delay under initial and optimized contact plan is shown in Fig. 7. It can be seen from Fig. 7 that the delay of CGR under optimized contact plan is improved compared to that under initial contact plan.

We then vary the message inter-arrival time, from 8 s to 0.5 s, to simulated different network loads. The delay performance of CGR under initial and optimized contact plan is shown in Fig. 8, from which it can be seen that the delay of CGR under optimized contact plan is also improved under different network loads.

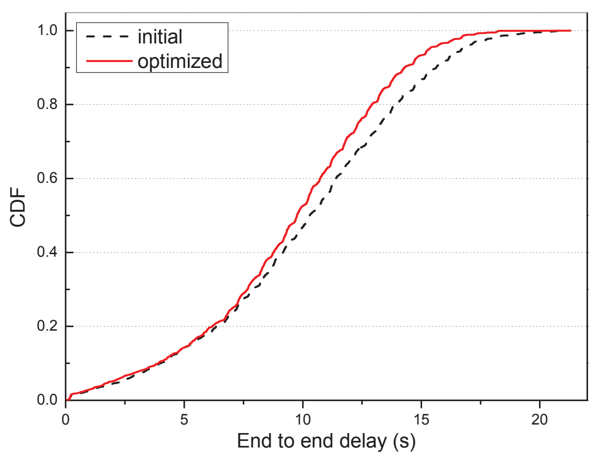


Figure 7 Delay CDF of CGR under initial and optimized contact plan.

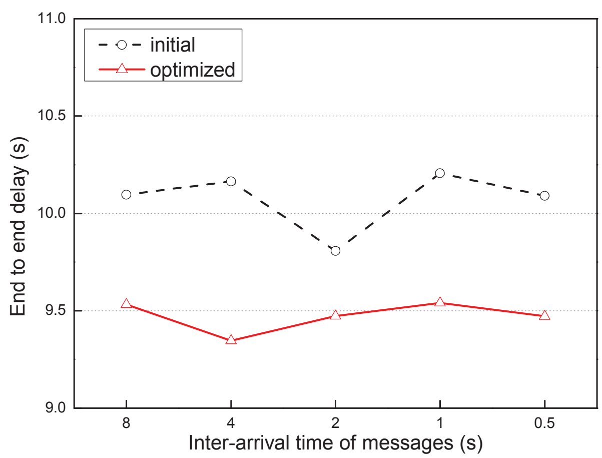


Figure 8 Delay of CGR under initial and optimized contact plan with varying network loads.

VI. CONCLUSION

The contact plan design of navigation satellite networks should accommodate both inter-satellite ranging and inter-satellite communication requirements. In this paper, we first present a topology handling scheme based on FSA and formulate the contact plan design problem as a constraint optimization problem. Then, a heuristic algorithm based on simulated annealing is proposed to solve the problem. Simulation results indicate that the proposed contact plan design method can be used to generate a delay-improved contact plan and the delay of CGR under optimized contact plan is improved than that under initial contact plan.

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