위성간 링크가 있는 위성군집시스템의 트래픽 스케줄링*

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Traffic Scheduling Algorithms for a SS/TDMA Cluster with Inter-Satellite Links*

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■ Abstract ■

The traffic scheduling problem for a satellite cluster with an arbitrary number of satellites is considered, which is one of the most interesting problems in the satellite communication scheduling area. This problem is to find a time slot assignment maximizing the transponder utilization for a satellite cluster. This problem is known to be NP-complete, and several heuristic algorithms have been proposed. In this paper, we suggest new efficient algorithms for this problem, which have less time complexity than the best existing one and provide much better solution quality. Extensive simulation results are reported.

Keyword : Satellite Switched TDMA(SS/TDMA), Time Slot Assignment(TSA), Inter-Satellite Links(ISLs)

1. Introduction

A satellite switched time division multiple access (SS/TDMA) system consists of a multi-beam antenna to cover several geographically distributed zones, an on-board switch to provide

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interconnections between the different zones, and a control unit to supervise system operations. The transmissions consist of constantly repeated TDMA time frames, each of which is divided into several smaller intervals called time slots. Each time slot has, corresponding to it, a configuration of the on-board switch that permits a certain amount of traffic to be transmitted. Single satellite SS/TDMA systems have been extensively studied under various optimization criterions [2, 3, 5-9, 11, 12].

In many practical situations, ground stations exchanging traffic are not always visible by the same satellite. Current practices involve either the use of ground communication lines or rerouting the traffic via an intermediate ground station which is in the line of sight of two satellites, one visible by the transmitter and the other visible by the receiver. In both cases, extra earth resources are used, thus reducing the total efficiency of the system. A more efficient solution for the above problem is the interconnection of satellites by inter-satellite links (ISL), creating a satellite communication network (Satellite Cluster) [1, 4, 10, 13]. The ISL system has a lot of good characteristics that can be utilized for supporting the existing systems [4]. Therefore SS/TDMA satellites with no on-board buffering, interconnected through inter-satellite links, are very promising. Indeed, INTELSAT has a couple of SS/TDMA networks in operation.

The performance of this satellite cluster system depends on several factors. The very important one is a proper assignment of traffic to time slots so that transmission conflicts are avoided. The objective of this time slot assignment is to schedule all the traffic in time slots with the maximum transponder utilization. For this assignment, we should account not only for the single satellite SS/TDMA scheduling constraints but also for additional constraints. Specifically, the continuous assignment from the source earth zone to the destination earth zone through the ISL should account for 1) transmission conflicts on the ISL's and 2) the traffic arriving from the ISL should be immediately switched to the appropriate downlink.

It has been proven that the time slot assignment problem for a satellite cluster with an arbitrary number of satellites is NP-complete, even for quite restricted inter-satellite link patterns and simplified models [1]. This means that the problem can be optimally solved only by algorithms that run in a time which grows as an exponential function in the size of the traffic matrix. Heuristic algorithms were presented in [1] for two satellites, each covering similar number of disjoint ground stations, and one ISL. In [4], presented was a heuristic algorithm, Heuristic ISL, for a quite generalized system. The algorithm is based on the algorithm for openshop scheduling problem, and has $O(rM^2)$ computational complexity, where r is the number of non-zero elements in the traffic matrix and M is the number of geographical zones. Kim *et al.* [10] suggested a new efficient algorithm, SCS, for a generalized model, where each satellite has an arbitrary number of transponders. However, the quality of its solutions is not quite satisfactory.

In this paper, we suggest new efficient algorithms for the SS/TDMA time slot assignment problem for a satellite cluster. The basic ideas of our algorithms is to sort ordered uplink and downlink zone pairs by two key factors traffic density and transponder/ISL capacity, and to sequentially select zone pairs satisfying transponder/ISL capacity constraints. Simulation results show that our algorithms generate much better solutions than other compared algorithms. Furthermore, the computational complexity of our algorithms is $O(r^2)$, which is smaller than the previous algorithms since r is much less than M^2 in general.

This paper is organized in the following way. The problem formulation and a theoretical lower bound on the switching duration are given in Section 2. Section 3 presents our heuristic algorithms. In Section 4, extensive computational test results of our algorithms are reported and compared with other existing algorithms. Section 5 concludes the paper.

2. Problem Formulation

We consider a cluster consisting of S satellites, $C=\{1,2,\cdots,S\}$, and a set of M disjoint geographical zones, $Z=\{1,2,\cdots,M\}$. Let us denote by Z_p the set of geographical zones which satellite p in the cluster covers. Here, Z_p is a subset of Z and the number of geographical zones in Z_p is denoted by M_p. We assume that each zone is covered by only one satellite. Hence, $Z_p \cap Z_q = \emptyset$ for two different satellites p and q. All uplinks and downlinks are assumed to have equal bandwidth. For two different satellites p and q, there are l_{pq} inter-satellite links from satellite p to satellite q. In addition, there are l_{pp} transponders in satellite p.

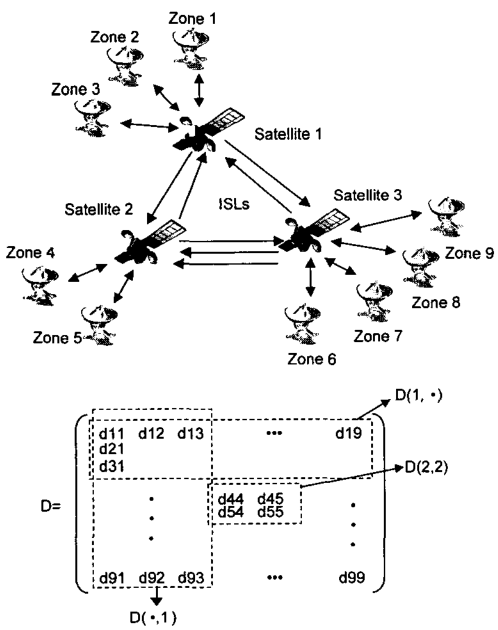
The traffic demand is characterized by an $M \times M$ matrix D with entry d_{ij} representing the amount of traffic from uplink beam (source zone) i to downlink beam (destination zone) j, measured in time slot units. For two different zones i and j visible by two different satellites, respectively, if the two satellites are not interconnected by ISL's, then d_{ij} and d_{ji} are set to 0. We denote by $D(p, q)$ the $M_p \times M_q$ submatrix of D representing the traffic between zones visible by satellite p and zones visible by satellite q. Of course $D(p, p)$ is the $M_p \times M_p$ submatrix of M representing the traffic between zones visible by satellite p alone. We refer to $D(p, q)$ as the *inter-satellite submatrix.* Note that the transmission of the traffic in the inter-satellite submatrix $D(p, q)$ requires both a transponder and an ISL simultaneously. $D(p, \cdot)$ is $M_p \times M$ submatrix of D representing the traffic originating from zones in Z_p. Also $D(\cdot, q)$ is $M \times M_q$ submatrix of D representing the traffic arriving to zones in Z_q. [Figure 1] shows an example of a satellite cluster and the corresponding traffic matrix.

The scheduling algorithm has to decompose the given traffic matrix D into distinct *switching matrices*, $D = D_1 + D_2 + \cdots + D_n$ where n denotes the number of switching configurations. Such a matrix characterizes a particular switching configuration and its corresponding traffic load being switched without conflict. The largest entry in a switching matrix D_i dictates the *switching duration* of D_i denoted by L_i. The *total duration* needed to schedule the complete traffic matrix D is given by $L = L_1 + L_2 + \cdots + L_n$. A schedule for D is *optimal* if it achieves maximum transponder utilization among all the possible schedules for D. It has been shown [2, 5] that this is equivalent to minimize the schedule length, L.

The traffic scheduling problem, therefore, is as follows :

$$\begin{aligned} Minimize\ & L = L_1 + L_2 + \cdots + L_n \\ s.t.\ & D = D_1 + D_2 + \cdots + D_n \end{aligned},$$

where D_i must be an $M \times M$ matrix with at most one positive entry in each row and column, at most l_{pq} positive entries in each submatrix corresponding to $D(p, q)$ where $p \neq q$, and at most $l_{pq}(l_{qq})$ positive entries in each submatrix corresponding to $D(p, \cdot)(D(\cdot, q))$, respectively. These constraints ensure D_i a switching matrix that is conflict free.



[Figure 1] A satellite cluster (S=3, M=9) and the corresponding traffic matrix D

Bertossi, *et al.* [1] considered a special case where there are two satellites, each has M_p transponders and one ISL. Ganz, *et al.* [4] considered the case where there are an arbitrary number of satellites and each satellite p in the cluster has M_p transponders and an arbitrary number of ISL's. Kim, *et al.* [10] considered the case where there are an arbitrary number of satellites and each satellite p has $l_{pp}(1 \leq l_{pp} \leq M_p)$transponders and an arbitrary number of ISL's.

The following Theorem 1 gives the theoretical *lower bound* on the minimal duration. We denote by r_i the sum of entries in the ith row of the traffic matrix D and by c_j the sum of entries in the j th column of D. Let $T(p, q)$ denote the amount of traffic in the submatrix $D(p, q)$, that is, the sum of all entries in $D(p, q)$. Let $T(p, \cdot)$ $(T(\cdot, q))$ denote the amount of traffic in the submatrix $D(p, \cdot)(D(\cdot, q))$, respectively.

Theorem 1 : Any schedule for D has length not smaller than LB :

$$LB = \max \left\{ \begin{array}{c} \max\limits_{1 \le i \le M} \{r_i\};\ \max\limits_{1 \le i \le M} \{c_i\}; \\ \max\limits_{1 \le p, q \le S, p \neq q} \left\{ \left\lceil \dfrac{T(p,q)}{l_{pq}} \right\rceil \right\}; \\ \max\limits_{1 \le p \le S} \left\{ \left\lceil \dfrac{T(p,\cdot)}{l_{pp}} \right\rceil \right\};\ \max\limits_{1 \le q \le S} \left\{ \left\lceil \dfrac{T(\cdot,q)}{l_{qq}} \right\rceil \right\} \end{array} \right\},$$

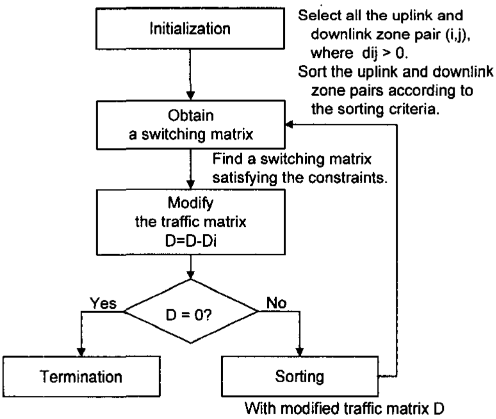
where $\lceil x \rceil$ is the smallest integer greater than or equal to x. For proof, refer to [10].

3. Time Slot Scheduling Algorithms

The optimal time slot assignment problem is known to be NP-complete [1]. In this paper, we present new heuristic algorithms. Two key factors influencing efficient time slot assignments are traffic density and transponder/ISL capacity.

The basic idea of our algorithms is to sort ordered uplink and downlink zone pairs (i, j)'s by these two factors, where $i, j \in Z$, and to sequentially select pairs satisfying transponder/ISL capacity constraints. We present two heuristic algorithms with different sorting criteria. The first algorithm **MTFS** (maximum traffic first scheduling) gives priority to the traffic density, and the second algorithm **MCFS** (minimum capacity first scheduling) gives priority to the transponder/ISL capacity.

[Figure 2] describes the flow of our algorithms in brief. These algorithms are described below in more detail. Each algorithm consists of two parts. One is to obtain a switching matrix, the other is to sort the traffic matrix according to the sorting criteria.



[Figure 2] A brief description of the algorithm flow

MTFS (Maximum Traffic First Scheduling)

Step 0. (Initialization)

(0.0) Let $\{d_{ij}\}$ and $\{l_{pq}\}$ be a given $M \times M$ traffic matrix and a given $S \times S$ transponder/ISL capacity matrix, respectively. Let $\bar{k}$ be the number of nonzero elements of $\{d_{ij}\}$. Let $I = \{(i, j) \mid d_{ij} \neq 0; i, j \in Z\}$, where (i_k, j_k) represents the kth element of I. Set $n = 1$.

(0.1) Sort I according to the descending order of traffic density d_{ij} (the first criterion) and the ascending order of transponder/ISL capacity $l_{s(i),s(j)}$ (the second criterion), where $s(i)$ represents the satellite that covers the zone i.

Step 1. (Obtaining a switching matrix)

(1.0) Set $t_p^u = l_{pp}$ and $t_p^d = l_{pp}$ for all $p \in C$ where t_p^u and t_p^d are the numbers of available transponders in satellite p for the uplink and downlink communications, respectively. Set $ul_i = 0$ and $dl_j = 0$ for all zone $i, j \in Z$, and set $e_k = 0$ for $1 \le k \le \bar{k}$. Set $k = 1$, $g = 0$ and $d^* = \infty$.

(1.1) If ($ul_{i_k} = 0, dl_{j_k} = 0$), ($t^u_{s(i_k)} > 0$, $t^d_{s(j_k)} > 0$) and ($l_{s(i_k),s(j_k)} > 0$), then go to Step (1.1.0). Otherwise, go to Step (1.2).

(1.1.0) Set $g = g + 1$, $(i^g, j^g) = (i_k, j_k)$, $\bar{d}_{i^g, j^g} = d_{i_k, j_k}$, $e_k = 1$, $ul_{i_k} = 1$ and $dl_{j_k} = 1$. If $d_{i_k, j_k} < d^*$ then $d^* = d_{i_k, j_k}$.

(1.1.1) Set $t^u_{s(i_k)} = t^u_{s(i_k)} - 1$ and $t^d_{s(j_k)} = t^d_{s(j_k)} - 1$. Set $l_{s(i_k),s(j_k)} = l_{s(i_k),s(j_k)} - 1$ if $s(i_k) \neq s(j_k)$. Go to Step (1.2).

(1.2) If $k < \bar{k}$, then replace k, with $k+1$, and go to Step (1.1). Otherwise, set $\bar{g} = g$ and form a switching matrix D_n.

The (i^g, j^g)th element of D_n has the value d^* for $g = 1, 2, \cdots, \bar{g}$, and other elements have the value 0. Set $n = n + 1$ and go to Step 2.

Step 2. (Sorting)

(2.0) Set $\bar{d}_{i^g, j^g} = \bar{d}_{i^g, j^g} - d^*$, if $\bar{d}_{i^g, j^g} = 0$ then the pair (i^g, j^g) is extracted, for $1 \le g \le \bar{g}$. Decrease $\bar{g}$ by the number of extracted pairs. Initialize the transponder/ISL capacity matrix $\{l_{pq}\}$. Set $k = 1, h = 0$ and $g = 1$.

(2.1) If $e_k = 1$, then replace h with $h + 1$, and go to Step (2.2). Otherwise, go to Step (2.1.0).

(2.1.0) If $(g \le \bar{g})$ and $((i^g, j^g) > (i_k, j_k))$, then go to Step (2.1.1). Otherwise, go to Step (2.1.2).

(2.1.1) Set $(i_{k-h}, j_{k-h}) = (i^g, j^g)$, $d_{i_{k-h}, j_{k-h}} = \bar{d}_{i^g, j^g}$, $h = h - 1$ and $g = g + 1$. Go to Step (2.1.0).

(2.1.2) Set $(i_{k-h}, j_{k-h}) = (i^g, j^g)$, $d_{i_{k-h}, j_{k-h}} = d_{i_k, j_k}$. Go to Step (2.2).

(2.2) Set $k = k + 1$. If $k \le \bar{k}$, then go to Step (2.1). Otherwise, if $g \le \bar{g}$, then set $(i_{k-h}, j_{k-h}) = (i^g, j^g)$, $d_{i_{k-h}, j_{k-h}} = \bar{d}_{i^g, j^g}$, $h = h - 1$ and $g = g + 1$ until $g > \bar{g}$. Go to Step 3.

Step 3. (Termination) Set $\bar{k} = \bar{k} - h$. If $\bar{k} = 0$ then terminate, otherwise, go to Step 1.

In Step 1, $ul_i = 1(dl_j = 1)$ if the uplink zone i is selected (downlink zone j is selected) and $ul_i = 0(dl_j = 0)$ otherwise. The paramete $e_k = 1$ if the kth element (i_k, j_k) of I is selected and $e_k = 0$ otherwise. Uplink and downlink zone pairs selected for obtaining the current switching matrix are (i^g, j^g), $g = 1, 2, \cdots, \bar{g}$. Step (1.1.1) updates the numbers of available transponders and ISLs. In Step (2.1.0), the equation $((i^g, j^g) > (i_k, j_k))$ means either $(\bar{d}_{i^g, j^g} > d_{i_k, j_k})$ or $(\bar{d}_{i^g, j^g} > d_{i_k, j_k}, l_{s(i^g), s(j^g)} < l_{s(i_k), s(j_k)})$.

The second algorithm MCFS is identical to MTFS except Step (0.1) and the meaning of $((i^g, j^g) > (i_k, j_k))$ in Step (2.1.0). Here, the equation $((i^g, j^g) > (i_k, j_k))$ means either or $(l_{s(i^g), s(j^g)} < l_{s(i_k), s(j_k)})$, or $(l_{s(i^g), s(j^g)} = l_{s(i_k), s(j_k)}, \bar{d}_{i^g, j^g} > d_{i_k, j_k})$. Step (0.1) of the algorithm MCFS is as follows :

MCFS (Minimum Capacity First Scheduling)

(0.1) Sort I according to the ascending order of transponder/ISL capacity $l_{s(i), s(j)}$ (the first criterion) and the descending order of traffic density d_{ij} (the second criterion).

The following Theorem 2 presents the worst case overall time complexity of the algorithms MTFS and MCFS.

Theorem 2 : The worst case overall time complexity of the algorithms MTFS and MCFS is $O(r^2)$, where r is the number of non-zero entries in D.

Proof. We, first, calculate the worst-case overall complexity of the algorithm MTFS. $O(r \log r)$ time is needed to sort I initially. $O(r)$ iterations of steps (1.1) and (2.1) are needed to obtain a switching matrix and to sort I additionally. In the worst case, the number of switching matrices generated and additional sorting processes are $O(r)$, since at least one non-zero entry is entirely scheduled in each switching matrix. Thus the worst-case overall time complexity of MTFS is $O(r\log r + r^2 + r^2) = O(r^2)$. Similarly, the worst-case overall time complexity of MCFS is. $O(r^2)$.

4. Simulation Results

All compared algorithms have been implemented in Pascal and simulation tests have been performed. Test examples have $S = 2, 3, 4$, $M = 6, 8, 12$. For each case we have applied all compared algorithms to 100 traffic matrices containing integers randomly generated from a uniform distribution between 0 and u, $u = 5, 10, 20$. This random generation format is exactly the same as that in [4] and [10]. And the number of transponders or inter-satellite links $\{l_{pq}\}$'s for two, three and four satellites are given as, respectively,

$$\begin{pmatrix} 3 & 1 \\ 1 & 2 \end{pmatrix}, \begin{pmatrix} 3 & 1 & 1 \\ 1 & 2 & 1 \\ 1 & 2 & 4 \end{pmatrix} and \begin{pmatrix} 2 & 1 & 2 & 1 \\ 1 & 3 & 1 & 1 \\ 2 & 1 & 3 & 1 \\ 1 & 1 & 1 & 3 \end{pmatrix}.$$

These $\{l_{pq}\}$'s are the same as that in [10]. <Table 1> shows the simulation results for

〈Table 1〉 Computational Results

u[a]	LB[b]	MHI	SCS	MTFS	MCFS
		(1) S = 2, M = 6			
5	26.49	29.43[c](11.73[d]) (19.40[e])	28.69[c](9.98[d]) (20.21[e])	26.74[c](0.94[d]) (18.74e)	26.75[c](0.98[d]) (18.89[e])
10	51.19	56.10(10.65) (25.62)	56.06(9.83) (25.93)	51.72 (1.04) (24.26)	51.50(0.61) (24.40)
20	103.80	113.74(10.55) (30.16)	113.18(9.38) (30.62)	105.86 (1.98) (29.76)	104.11(0.30) (29.39)
		(2) S = 3, M = 12			
5	63.97	69.36(8.91) (56.13)	66.68(4.14) (55.82)	64.22(0.39) (51.33)	64.45(0.75) (46.99)
10	125.19	136.90(8.90) (83.53)	130.82(3.76) (83.84)	125.45(0.21) (72.37)	125.87(0.54) (67.66)
20	252.20	273.60(8.63) (107.51)	261.25(3.38) (107.39)	252.65(0.18) (90.83)	253.57(0.54) (91.15)
		(3) S = 4, M = 12			
5	48.48	58.12(20.03) (47.39)	51.67(6.61) (45.13)	48.72(0.50) (40.40)	48.75(0.56) (42.78)
10	95.12	115.39(21.14) (74.28)	101.31(6.20) (71.17)	95.47(0.37) (62.22)	95.63(0.54) (65.49)
20	190.18	233.12(22.92) (99.67)	203.66(7.73) (97.42)	190.63(0.24) (84.75)	191.27(0.57) (95.50)

Note) a : the range of traffic is [0, u]. b : the average lower bound. c : the average duration.
d : the average surplus percentage from the lower bound (%)={(average duration−LB)/LB}×100.
e : the average number of switching configurations.

the above systems. In <Table 1>, we report the lower bound of each problem. We also report the average duration and the average surplus percentage from the lower bound for all compared algorithms.

<Table 1> shows that our algorithms MTFS and MCFS need much less duration than the modified Heuristic ISL (MHI) [10] and SCS [10]. MCFS is better than MTFS in case of two-satellite systems, and MTFS is better than MCFS in other cases. In each case, MTFS and MCFS generate a switching configuration whose duration is very close to its theoretic lower bound. Hence, we can conclude that all configurations generated by MTFS and MCFS are very close to optimal solutions.

In addition, <Table 1> shows the average number of switching configurations since this could be another important factor in the traffic scheduling. We can see our algorithms need much smaller number of switching configurations than MHI and SCS in all cases.

5. Conclusions

We have suggested new efficient algorithms that find a time slot assignment for a satellite cluster. Simulation results show that our presented algorithms provide a solution very close to the optimal schedule. In addition, they have low computational complexity.

This type of scheduling will be more interesting problems in the low earth orbit satellite communication systems, in which there are several tens of satellites. Our algorithms can be easily applicable to the LEO satellite cluster systems. However, in this case, an efficient distributed algorithm could be more powerful, because of the problem size. It would be interesting to transform our algorithm into a distributed one in order to deal with this complex case.

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