AN OPTIMAL TIME SLOT ASSIGNMENT ALGORITHM IN SS/TDMA SYSTEM WITH INTERSATELLITE LINK

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RÉSUMÉ

Dans ce travil, on discute le système de commutation par satellite utilisant l'accès multiple a repartition dans le temps dans un amas de deux satellites. On assume que le deux satelittes sont inter-communiquées par une liaison entresatellite. En 1987, Bertossi et les autres ont proposé un algorithme optimal de commutation qui etablit l'horaire de connexion des crèneaux temporelles de chaque liaison. Dans cet aritcle, on montre comment cet algorithme peut être appliqué dans un cas plus générale où le nombre des liaison soit Terre-vers-satellite ou satellite-vers-Terre est différent pour chaque satellite. En plus, chaque liaison soit Terre-vers-satellite ou satellite-vers-Terre peut avoir une largeur de bande différente. Ici, un exemple du cas général est demontré en détaille.

ABSTRACT

Bertossi et al (1987) have proposed an optimal switching algorithm using inter-satellite link in a cluster of two satellites. They considered the case where each satellite in the cluster has the same number of uplink and downlink beams. Moreover, all beams have the same bandwidth. The present work considers the case where the number of uplink and downlink beams are not the same, and each beam can have different bandwidth. The details of the scheduling algorithm are given together with an illustrative example. The main idea of the proposed algorithm is to transform the intersatellite scheduling problem into a general scheduling problem as it will be explained.

1. *INTRODUCTION*

Satellite switched time division multiple access (SS/TDMA) system combines the efficiency and flexibility of TDMA access together with an efficient use of RF spectrum [1]-[7]. On the other hand, PUCCIO et al [8] have studied the possibility of interconnecting the EUTELSAT Multiservice System (SMS) and the INTELSAT Business Service (IBS) via intesatellite link (ISL) since both systems have the same access and common earth station standards.

The main objective of the present work is how to avoid transmission conflicts in an SS/TDMA system using ISL. This can be achieved through proper assignment of the traffic to different slots. We consider a cluster of two satellites. All the traffic received by a satellite is assumed to be immediately sent to ground zones or over the ISL according to on-board switching configurations, i.e., the satellite has no storing facility.

The optimal algorithm , presented here, is based on the optimal algorithm proposed by BERTOSSI et al [9]. We refer to this algorithm as *ISL Optimal Algorithm*. The *ISL Optimal Algorithm* considers the case where each of the two satellites has the same number of uplink and downlink beams, and all are of equal bandwidth. We transfer the problem of a cluster of two satellites interconnected via ISL into a general scheduling problem where we can use arbitrary number of uplink and downlink beams with different bandwidths.

2. *NOTATIONS AND DEFINITIONS*

Consider a system of two SS/TDMA satellites where the ground stations that exchange traffic may not be visible by the same satellite, therefore the two satellites are interconnected via ISL. An ISL traffic matrix *D* for a cluster of two satellites can be defined as an M*N matrix, where M is the sum of uplink beams of both satellites, i.e., $M = M_1 + M_2$. Similarly, N is the sum of downlink beams of both satellites, i.e., $N = N_1 + N_2$. Entry d_{ij} in *D* represents the amount of traffic that zone i must transmit to zone j. If zone i is visible by the first satellite, zone j by the second satellite the entry d_{ij} represents the amount of traffic from zone i to zone j through the ISL. We assume that each of the two satellite in the cluster has variable bandwidth beams, i.e., uplink beam i has bandwidth a_i, and downlink beam j has bandwidth b_j. In our case we may allow several entries in any row or any column as long as the sum of all entries of row i is less or equal to a_i, and the sum of all entries of column j is less or equal to b_j. So, we can represent the cluster uplink bandwidths by the speed vector $\underline{a} = \{\underline{a}_1 | \underline{a}_2\} = \{a_1\ a_2 \ldots a_M\}$, where $\underline{a}_1$ and $\underline{a}_2$ are the speed vectors of the two satellites . Similarly, the cluster downlink speed vector is $\underline{b} = \{\underline{b}_1 | \underline{b}_2\} = \{ b_1\ b_2 \ldots b_N\}$, where $\underline{b}_1$ and $\underline{b}_2$ are the downlink speed vectors of the two satellites. Let r_i and c_j represent the ith row sum and the jth sum respectively of the ISL matrix *D*. An *abSM* switching matrix [6] is defined as an (M*N) matrix with non negative entries such that; $r_i \leqslant a_i$, $i = 1, 2, .., M$, and $c_j \leqslant b_j$, $j = 1, 2, .., N$. A Quasi doubly stochastic (*QDS*) matrix [6] is defined as an (N*N) matrix for which ; $c_j = s$, $j = 1,2,..,N$ and $r_i = s$, $i = 1,2,..,M$, where s is a some positive integer called the line sum of the matrix. The normalized quasi doubly stochastic (*NQDS*) matrix is defined as an (M*N) matrix with $c_j/b_j = S$, $j = 1,2,..,N$ and $r_i/a_i = S$, $i = 1,2,..,M$, where S is a some positive integer called the normalized line sum of the matrix. The traffic of the matrix is defined as the sum of all entries in that matrix.

Let *S(1,2)* be the ($M_1 * N_2$) submatrix of the matrix *D* representing the traffic between zones visible by the first satellite and the second satellite, while *S(1,1)* represent traffic between zones visible by the first satellite alone. Similarly *S(2,1)* is the ($M_2 * N_1$) submatrix of *D* representing the traffic between zones visible by the second satellite to zones visible by the first satellite , while *S(2,2)* represents traffic between zones visible by the second satellite alone. *S(1,2)* and *S(2,1)* are called intersatellite submatrices [9]. Let T(h,k) be the amount of traffic in the intersatellite submatrix *S(h,k)*,i.e., the sum of all entries in *S(h,k)*.

A time slot assignment (or transmission schedule) of an ISL traffic matrix *D* is a decomposition of *D* into switching matrices:

$$D = D_1 + D_2 + \ldots + D_t \qquad (1)$$

where D_i is an (M*N) matrix representing the traffic that can be transmitted without conflicts and switch reconfigurations. The largest entry in D_i, say L_i, dictates its duration, i.e., the number of consecutive time slots needed to transmit D_i. The total duration needed to schedule the whole traffic matrix *D* is

$$L = L_1 + L_2 + \ldots. + L_t \qquad (2)$$

To minimize the total duration L, the number of switching modes must be kept as small as possible., i.e., an optimal schedule for *D* should result in minimum duration . For the general case considered here, the lower bound S on the duration of any schedule for the ISL traffic matrix *D* given in [9] can be rewritten as

$$S = \max \{ T(1,2),\ T(2,1),\ \max_{1 \leqslant i \leqslant M} \lceil r_i/a_i \rceil,\ \max_{1 \leqslant j \leqslant N} \lceil c_j/b_j \rceil \} \qquad (3)$$

where $\lceil x \rceil$ is the least integer greater or equal to x

3. *PROBLEM FORMULATION*

In a cluster of two satellites interconnected via intersatellite link with ISL traffic matrix *D*(M*N), it is required to find the time slot assignment of this ISL traffic matrix *D* which is the decomposition of *D* into switching matrices $D = D_1 + D_2 + \ldots + D_t$ such that:

- Each switching matrix D_i has at most a number of nonzero entries in each row equal to its corresponding element in the uplink speed vector $\underline{a}$
- D_i has at most a number of nonzero entries in each column equal to its corresponding element in the downlink speed vector $\underline{b}$
- Each D_i has at most one nonzero entry in each intersatellite submatrix.
- The length of the schedule is minimum

4. *GENERAL OPTIMAL ALGORITHM*

Assume that the ISL traffic matrix *D* is an *NQDS* matrix. This implies that [6]:

$$\sum_{i=1}^{M} a_i = \sum_{j=1}^{N} b_j = H \qquad (4)$$

The decomposition procedure starts by constructing an (H*H) *QDS* matrix from the (M*N) *NQDS* matrix of line sum S. The construction of the *QDS* matrix of line sum S from matrix *D* is based on an expansion process. This expansion process uses two algorithms; Column expansion algorithm, and Row expansion algorithm [6]. The details of Column and Row expansion algorithms are given in the Appendix. The Column expansion algorithm converts matrix *D* into an (M*H) matrix *B*. The matrix *B* has the same traffic and line sum as the traffic matrix *D*. The Row expansion algorithm operates on *B* and transforms it into an (H*H) matrix *A*. The expansion process simply distributes the entry $[d_{ij}]$ in traffic matrix *D* into ($a_i * b_j$) submatrix of *A*. At this point we can apply the *ISL Optimal Algorithm* to matrix *A* to find the corresponding switching matrices $A_1, A_2, \ldots, A_t$. The *ISL Optimal algorithm* is of the branch and bound type. This algorithm produces optimal schedule in a reasonable time when the traffic matrix is not large or has a particular structure of its nonzero entries. To get the original matrix *D*, the inverse of the expansion process is performed on each A_i by shrinking each ($a_i * b_j$) submatrix into a single entry. This is done in two steps; first the (H*H) matrix *A* is compressed to an (M*H) matrix by adding the rows which have been expanded in Row expansion process, then the (H*M) matrix is compressed to an (M*N) matrix by adding the the columns which have been expanded in Column expansion process. This process is called Row and Column Compression process. In this way, we can get the decomposition of the *NQDS* traffic matrix *D*.

If the original ISL traffic matrix *D* is not an *NQDS* matrix, we convert it first into an (M+1*N+1) *NQDS* matrix *Q*. This can be achieved using the Completion algorithm [6]. This requires the addition of dummy traffic to the original traffic matrix *D*. The dummy traffic is removed at the end of the switching algorithm.

We can summarize the general scheduling algorithm in the following steps:

Step (1):
If the matrix *D* is not *NQDS* matrix, use the Completion algorithm to add dummy traffic to the given matrix *D* to convert it to a *NQDS* matrix *Q*.

Step (2):
Use the Column expansion algorithm followed by the Row expansion algorithm to expand the *NQDS* matrix *Q* into a *QDS* matrix *A*.

Step (3):
Apply the *ISL OPTIMAL Algorithm* on matrix *A* to find the corresponding switching matrices $A_1, A_2, \ldots, A_t$

Step (4):
Use the Row compression algorithm followed by the Column compression algorithm to find the switching matrices $Q_1, Q_2, \ldots, Q_t$

Step(5):
Remove the dummy traffic (if it is added in the first step) from $Q_1, Q_2, \ldots, Q_t$ to get the switching matrices $D_1, D_2, \ldots, D_t$.

5. *EXAMPLE OF GENERAL OPTIMAL ALGORITHM*

In this section the steps of the proposed time assignment algorithm in case of a cluster of two satellites will be illustrated using a simple example.

Given a cluster of two satellites interconnected via ISL. For the first satellite, the number of uplink beams M_1 and downlink beams N_1 are 3 and 2 respectively. Its corresponding speed vectors are:

$$\underline{a}_1 = (\ 1\ 2\ 1\ )$$
$$\underline{b}_1 = (\ 2\ 2\ )$$

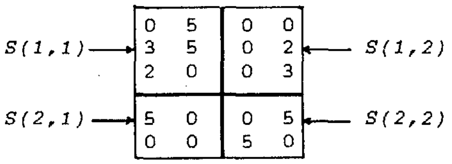
The second satellite has a number of uplink beams $M_2 = 2$ and a number of downlink beams $N_2 = 2$. The uplink and downlink speed vectors are:

$$\underline{a}_2 = (\ 2\ 1\ )$$
$$\underline{b}_2 = (\ 1\ 2\ )$$

The corresponding uplink and downlink speed vectors of the cluster are;

$$\underline{a} = \{\ 1\ 2\ 1\ 2\ 1\ \}$$
$$\underline{b} = \{\ 2\ 2\ 1\ 2\ \},$$

and the traffic matrix, *D*, of the cluster is;



Solution:

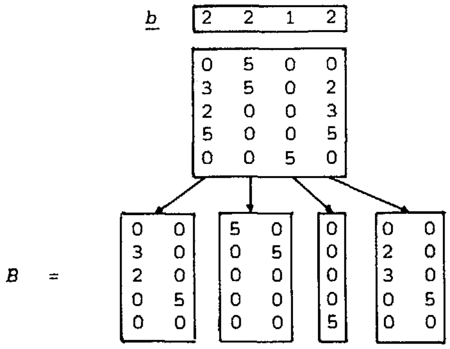
From equation (3), the lower bound S is;

$$S = \max \{\ T(1,2),\ T(2,1),\ \max_{1\leqslant i\leqslant M} \lceil r_i/a_i \rceil,\ \max_{1\leqslant j\leqslant N} \lceil c_j/b_j \rceil\ \}$$
$$= \max \{\ 5,\ 5,\ 5,\ 5\ \} = 5,$$

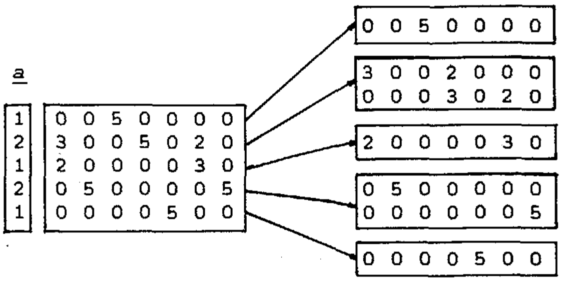
so the matrix *D* is *NQDS* matrix.

Step (1):
The matrix *D* is an *NQDS* matrix, so the completion algorithm will not be applied.

Step (2):
a- Column expansion algorithm:
Each column in matrix *D* is expanded into a matrix whose number of columns is equal to the corresponding element in $\underline{b}$.



b- Row expansion algorithm:
Each row in the matrix resultant from the column expansion process will be expanded to a matrix which has number of rows equal to its corresponding element in $\underline{a}$. This process leads to a matrix which has all line sums equal to S, i.e a *QDS* matrix.



The resultant matrix *A* is a *QDS* matrix:

$$A = \begin{bmatrix} 0&0&5&0&0&0&0\\ 3&0&0&2&0&0&0\\ 0&0&0&3&0&2&0\\ 2&0&0&0&0&3&0\\ 0&5&0&0&0&0&0\\ 0&0&0&0&0&0&5\\ 0&0&0&0&5&0&0 \end{bmatrix}$$

Step (3):
Using the *ISL Optimal Algorithm* to obtain the switching matrices for the matrix *A*; we get:

$$A_1 = \begin{bmatrix} 0&0&3&0&0&0&0\\ 3&0&0&0&0&0&0\\ 0&0&0&3&0&0&0\\ 0&0&0&0&0&3&0\\ 0&3&0&0&0&0&0\\ 0&0&0&0&0&0&3\\ 0&0&0&0&3&0&0 \end{bmatrix} \qquad A_2 = \begin{bmatrix} 0&0&2&0&0&0&0\\ 0&0&0&2&0&0&0\\ 0&0&0&0&0&2&0\\ 2&0&0&0&0&0&0\\ 0&2&0&0&0&0&0\\ 0&0&0&0&0&0&2\\ 0&0&0&0&2&0&0 \end{bmatrix}$$

Step (4):
Using the Row compression algorithm; we get:

$$\begin{bmatrix} 0&0&3&0&0&0&0\\ 3&0&0&3&0&0&0\\ 0&0&0&0&0&3&0\\ 0&3&0&0&0&0&3\\ 0&0&0&0&3&0&0 \end{bmatrix} \qquad \begin{bmatrix} 0&0&2&0&0&0&0\\ 0&0&0&2&0&2&0\\ 2&0&0&0&0&0&0\\ 0&2&0&0&0&0&2\\ 0&0&0&0&2&0&0 \end{bmatrix}$$

Using the Column compression algorithm, we get the final switching matrices for the original matrix *D*:

$$D_1 = \begin{bmatrix} 0&3&0&0\\ 3&3&0&0\\ 0&0&0&3\\ 3&0&0&3\\ 0&0&3&0 \end{bmatrix} \qquad D_2 = \begin{bmatrix} 0&2&0&0\\ 0&2&0&2\\ 2&0&0&0\\ 2&0&0&2\\ 0&0&2&0 \end{bmatrix}$$

Notice that:
* Each of the resultant switching matrices has at most one nonzero element in each of the intersatellite submatrices.
* Each of the resultant switching matrices has at most a_i nonzero entries in each row and at most b_j nonzero entry in each column.

Step (5):
We do not add any dummy traffic in the first step, so the switching matrices D_1 and D_2 represent the optimal decomposition of the traffic matrix D. From equation (2), the required transmission time, L, is 5. This is the optimal value determined by equation (3).

6. *REMARKS*

In this work, we showed how the *ISL Optimal Algorithm* proposed by BERTOSSI et al [1987] for a cluster of two satellites can be applied to the case where the number of uplink and downlink beams are not the same for each satellite and each beam has different bandwidth. The ISL scheduling problem is transferred into a general SS/TDMA scheduling problem. However the application of such method is still limited to the case where the propagation delay between the two satellites in the cluster is negligibly small with respect to the time slot duration. The proposed algorithm is no more valid when this is not the case.

The main objective of the present paper is to solve the assignment problem rather to prove that it is an NP-complete or not. The proposed algorithm achieved that objective and showed how the overall scheduling duration could be minimized. This also meant efficient use of transponder utilization time. However, the amount of computation time remained considerable even for a cluster of only two satellites.

APPENDIX

1- Column Expansion Algorithm

Expansion of the matrix D into (M*H) matrix B by expanding each column j in D into an $(M*b_j)$ matrix E_j as follows [6]:
Let c_m^E be the column sum of the mth column in E_j and r_k^E be the row sum of the kth row in E_j. Assuming first that all entries in E_j are zeroes, then we add the quantity x_{km},

$$x_{km} = \min (S - c_m^E , d_{kj} - r_k^E)$$

to the (k,m) entry in E_j; where d_{kj} represents the (k,j) entry in D. The process is completed if no nonzero x_{km} can be added.

The matrix E_j has the same traffic as the jth column in D and all column sums of E_j are equal to S, and the kth row sum of $E_j = [d_{kj}]$. We construct such an E_j matrix for every j, j=1,2,..,N, so we will have the matrices E_1, E_2,...,E_N which form a single (M*H) matrix B. The matrix B has the following properties:

i- B has the same traffic as D,
ii- all column sums in B are equal to S,
iii- all row sums in B are equal to the corresponding row sums in D.

2- Row Expansion Algorithm

This algorithm is similar to Column expansion algorithm except that it operates on the rows of B to obtain an (H*H) matrix A. Row i of B is expanded into $(a_i * H)$ matrix F_i. Let c_m^F be the sum of the mth column of F_i, and r_k^F be the sum of the kth row of F_i. We add the quantity x_{km},

$$x_{km} = \min (S - r_k^F, b_{im} - c_m^F)$$

to the (k,m) entry in F_i; where b_{ij} is the (i,j) entry in the matrix B. The process terminates when no nonzero quantity can be added. The matrices F_i, i=1,2,..M, will form the (H*H) row matrix A. The matrix A which is a *QDS* matrix, has the following properties:

i- A has the same traffic as D,
ii- all row and columns sums of A are equal to S.

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