An Optimal Switching Algorithm For Multibeam Satellite Systems With Variable Bandwidth Beams In the Presence Of Interference

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RESUME

On considère ici un système de commutation par satellite utilisant l'accès multiple a réparation dans le temps (AMRT). Le satellite a plusieurs antennes qui couvert des zones differentes. Soit le numbre de repeteurs a bord de satellite K, le numbre de liaisons Terre vers satellite M, et le numbre de liaisons satellite vers Terre N. Dans ce système, le satellite peut commuter des faiseaux à son bord. Donc, on peut rélier une liaison Terre vers satellite, par exemple, a liaison satellite vers Terre dans des endroits differents. Dans tel système, on doit considèrer l'effet d'interférence parmi les liaisons dans le même sens. On propose un algorithme optimal qui établit l'horaire de connexion des crèneaux de temps de chaque liaison. L'algorithme assure que tout le trafic peut être émit, sans conflit, pendant la trame d'AMRT.

SUMMARY

In a typical satellite switched time division multiple access (SS/TDMA) system, the TDMA frame is divided into several time slots, and each slot has a switching configuration permitting a certain amount of traffic to be transmitted. The system main objective is to ensure that all the traffic can be transmitted without conflict within the TDMA frame. The satellite has a number of spot beam antennas covering geographical distributed zones and a solid state RF switch on board to provide connections between the various uplink and downlink beams. A high gain antenna on board the satellite provides various spot beam coverage. This antenna may allow interconnectivity between uplink and downlink beams, i.e., substantial power from one beam may spoil over into a neighboring zone leading to what is called zone interference. The effect of zone interference has been studied in the special case of SS/TDMA system with N uplink and N downlink beams all of equal bandwidth and with at least N transponders on board.

In this work, we study the traffic scheduling problem with interfering beams in a more general SS/TDMA system. We consider a system with M uplink beams and N downlink beams, where uplink i has bandwidth β and downbeam j has bandwidth α. The maximum traffic which can be handled by the satellite (at any given time slot) is assumed to be K, $1 \leq K \leq \min(M,N)$. The interference between zones can be characterized by the graphs G_U and G_D where $G_U = (V,E)$ represents the interference on uplink beams, with vertex set V representing the M zones and edge set E containing an edge (v_i, v_j), $v_i, v_j \in V$ if and only if zone i interferes with zone j on uplink transmissions. Similarly, G_D represents the interference on the downlink beams. The traffic demand is characterized by the traffic matrix D. The transmission schedule is defined as the decomposition of the traffic matrix D into several switching matrices, i.e., $D = D_1 + D_2 + \ldots + D_L$, where D_i represents the transmissions in time slot i of the TDMA frame. The sequence $(D_1, D_2, \ldots, D_L)$ is the transmission schedule. We look for a feasible transmission schedule which never requires two interfering zones to transmit or receive simultaneously. This can be achieved if no D matrix contains entries on rows corresponding to adjacent vertices of G_U or on columns corresponding to adjacent vertices of G_D. The proposed algorithm provides the solution of this problem and it is optimal in the sense that it minimizes the transmission time for any given traffic matrix D.

I- Introduction:

The satellite-switched time division multiple access (SS/TDMA) system utilizes the merits of high gain spot beam antennas along with the efficient TDMA method of providing complete connectivity of coverage areas. In such a system, a satellite embodies several spot-beam antennas and a solid-state RF switch periodically switches the connections of uplink and downlink beams to facilitate inter connectivity of beam zones. A TDMA frame is divided into a number of switching modes, each switching mode is assigned a fixed on-board switch connection so that the traffic from various regions is routed to designated regions without conflict.

In an SS/TDMA network, all earth stations must share a given number of satellite transponders on a time base, it is desirable to maximize the transponder utilization according to the network traffic requirements. The time slot assignment problem then is to schedule the network burst traffic in a manner that maximizes the satellite transponder utilization with a minimum number of switching modes. More specifically, the traffic demand is characterized by a traffic matrix D, where entry d_{ij} represents the traffic demand from uplink beam i to downlink beam j, measured in units of slot time. A scheduling scheme then depicts a way to decompose the given traffic matrix D into distinct switching matrices i.e, $D = D_1 + D_2 + \ldots\ldots D_l$, where D_i is a matrix with its largest entry dictates the duration of a switching matrix $= |D_i|$. To maximize transponder utilization, one must minimize the total duration i.e., $\Sigma\, |D_i|$ needed to schedule (or switch) the complete traffic matrix D. On the other hand, the number of switching modes should be kept small. Let M and N denote, the number of uplink and downlink beams respectively. The proposed algorithm deals with the general system where variable bandwidth of uplink and downlink beams, are considered, i.e., uplink beam i has bandwidth α_i, and downlink beam j has bandwidth β_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 α_i, and the sum of all entries of column j is less or equal to β_j.

None of the algorithms discussed in [1] -[6] considers zone interference. However in practice side lobes in the antenna radiation paterns, insufficient antenna gain, or very small and closely packed zones may cause substational power from one spot beam into a neighbouring zone which is called zone interference. The proposed algorithm takes into account the presence of interference, i. e., the switching matrix D_i must not contain entries on rows which corresponds to interfering uplink zones or on columns which correspond to interfering downlink zones.

II- Notions And Definitions:

The uplink bandwidths are represented by the speed vector α, $\alpha = \{\alpha_1\ \alpha_2 \ldots\ldots \alpha_m\}$, where α_i is a positive integer representing the bandwidth of the i th uplink, similarly, the speed vector $\beta = [\ \beta_1\ \beta_2 \ldots\ldots \beta_n]$ represents the downlink bandwidths. The capacity of the satellite K is the maximum amount the satellite can carry in one time slot. Assume $1 \leqslant k \leqslant \min(\Sigma\ \alpha_i,\ \Sigma\ \beta_j)$, and let r_i and c_j represent the ith row sum and the jth sum respectively. An ($\alpha\beta$SM) is defined [7] as an (M*N) matrix with non negative entries such that; $c_j \leqslant \beta_j$ for $1 \leqslant j \leqslant N$ and, $r_i < \alpha_i$ for $1 \leqslant i \leqslant M$. A Quasi doubly stochastic (QDS) matrix [7] is defined as an (N*N) matrix for which $c_j = S$, $1 \leqslant j \leqslant N$ and $r_i = S$, $1 \leqslant i \leqslant M$, 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 $c_j/\beta_j = S$, $1 \leqslant j \leqslant N$ and $r_i/\alpha_i = S$, $1 \leqslant i \leqslant M$ 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 traffic matrix. The interference between zones is characterize by the graphs G_U and G_D [8]. $G_U = (V,E)$ represents the interference on uplink beams with vertex set V representing the M uplink zones and edge set E containing an edge (v_i, v_j), $v_i, v_j \in V$ if and only if zone i interferes with zone j on uplink transmission. Similarly $G_D = (V,E)$ defines the interference on the downlink beams. G_U and G_D can be identical, but we consider the general case where they are different.

III Problem Formulation:

The problem is; given a traffic matrix D (M*N) with uplink and down link speed vector α and β, satellite capacity K, and uplink and down link interference graphs G_U and G_D, find the decomposition of $D = D_1 + D_2 + \ldots D_l$ such that :

1) all the D_i's are $\alpha\beta$SM's with traffic not greater than K.
2) the number of switching matrices is minimized.
3) D1 must not contain entries on rows which corresponds to adjacent vertices of G_U or on columns which corresponds to adjacent vertices of G_D.

IV Column and Row Expansion Algorithms:

For a feasible schedule $D = D_1 + D_2 + \ldots D_l$ can never be smaller than S which is given by:

$$S = \max\left(\left\lceil \frac{T}{K} \right\rceil,\ \max_{1 \leqslant i \leqslant M} \left\lceil \frac{r_i}{\alpha_i} \right\rceil,\ \max_{1 \leqslant j \leqslant N} \left\lceil \frac{c_j}{\beta_j} \right\rceil \right)$$

where T is the total traffic in D and $\lceil X \rceil$ denotes the smallest integer greater or equal to X. From [8] and [9], an (M*N) NQDS matrix D with normalized line sum S can be expressed as sum of S-complete $\alpha\beta$SM's.

The proof of this theorem is based on the constructions of an (H*H) QDS matrix from the (M*N) NQDS matrix of line sum. The construction proceeds as follows:

(a) Column expansion algorithm:

Expansion of the matrix D into (M*H) matrix D' by expanding each column j in D into (M*β_j) matrix A_j as follows: Let c_{la} be the column sum of lth column in A_j and r_{ka} be the row sum of kth row in A_j. Assuming first that all entries in A_j are zeroes, then we add the quantity x_{kl} to the (k,l) entry in A_j where:

$$x_{kl} = \min (S - c_{la} , d_{kj} - r_{ka})$$

where d_{kj} represents the (k,j) entry in D. The process will be completed when no nonzero x_{kl} can be added.

The matrix A_j must have the same traffic as the jth column in D and all column sums of A_j is equal to S, and the kth row sum of $A_j = d_{kj}$. We construct such an A_j matrix for every j, $1 \leqslant j \leqslant N$ so we will have $A_1, A_2, \ldots, A_N$ which form a single $(M*H)$ matrix D' which has the same traffic as D and has all column sums = S, all row sums = row sums in D.

(b) row expansion algorithm:

The second step is a similar expansion but this time on the rows of D' to obtain an $(H*H)$ matrix D". Row i of D' is expanded into $(\alpha_i * H)$ matrix B_i. Let c_{lb}' be the sum of the lth column of B_i, and r_{kb}' be the sum of the kth row of B_i. We add x_{kl}' to the (k,l) entry in B_i where:

$$x_{kl}' = \min (S - r_{ka}', d_{il}' - c_{lb}')$$

where d_{il}' refers to the (i,l) entry in D'. The process terminates when no nonzero quantity can be added. The matrices B_i's will form the $(H*H)$ row matrix D" which has traffic equal to that of D' (which in turn is equal to that of D), and all rows and column sums of D are equal to S. Thus D" is QDS matrix.

D" can be expressed as the S permutation matrices $D_1", D_2", \ldots D_S"$, then we make compression to $D_i"$, $1 \leqslant i \leqslant S$, to get D_i' by first row compression algorithm followed by column compression algorithm for the D_i' to get D_i. Thus each D_i is an αßSM.

Now we assume that the given D $(M*N)$ matrix is not NQDS matrix, thus we must transform it to NQDS matrix using the compelition algorithm as follows:

* Create the Q $(M+1* N+1)$ matrix by adding extra row and extra column to D. For the extra column, assign

$$\beta_{N+1} = \sum_{i=1}^{M} \alpha_i - K$$

for the extra row, assign

$$\alpha_{M+1} = \sum_{j=1}^{N} \beta_j - K$$

Thus for the matrix Q, the vectors

$\alpha' = \{ \alpha_1, \alpha_2, \ldots, \alpha_{M+1} \}$, and

$\beta' = \{ \beta_1, \beta_2, \ldots, \beta_{N+1} \}$

Let r_{iq} = ith row sum of Q $1 \leqslant i \leqslant M+1$ and

e_{jq} = jth column sum of Q $1 \leqslant j \leqslant N+1$

Initially let $r_{M+1} = c_{N+1} = 0$, and $r_{iq} = r_i$, $c_{jq} = c_j$ $1 \leqslant i \leqslant M$, $1 \leqslant j \leqslant N$ where r_i, c_j refer to row sum and column sum of D respectively. Now, we add the quantity $x_{M+1,j}$ to entry $q_{M+1,j}$, for $i \leqslant j \leqslant n$ where

$$x_{M+1,j} = \min(\alpha_{M+1}S - r_{M+1,q} , \beta_jS - c_{jq})$$

The process terminates when no nonzero quantity can be added. Similarly we add entries to column N + 1, to entry $q_{i,N+1}$ $1 \leqslant i \leqslant M$ and $x_{i,N+1}$ where :

$$x_{i,N+1} = \min (\beta_{N+1}S - c_{N+1,q}', \alpha_iS - r_{iq})$$

We claim that, when this occurs, Q is an NQDS matrix.

* If Q is not NQDS matrix, consider the submatrix Q' of Q defined by the first M rows and the first N columns. To entry q_{ij}' in this submatrix add quantity x_{ij},

$$x_{ij} = \min (\beta_jS - c_{jq} , \alpha_iS - r_{iq})$$

This quantity is called a dummy traffic which will be removed at the end of the algorithm.

The process terminated when no nonzero entry can be add, thus Q is a NQDS matrix.

V The Optimal Algorithm:

Step (1)

From the uplink graph G_U add the rows of the given traffic matrix D which has interference to each other. Calculate the new α of the resulted row which will be equal to the sum of α's of these rows.

Step (2)

From the downlink graph G_D add the columns of the matrix (resulting from the previous step) which has interference to each others. Calculate the new ß of the resulted column which will be equal to the sum of ß 's of ß this columns. The result is the $(M*N)$ D' matrix.

Step (3)

If D' is not NQDS matrix, we apply the compelition algorithm to convert it to NQDS matrix w.r.t. S. The new matrix is called the Q matrix.

Step (4)

Expand the matrix Q to $(M+1*H)$ matrix using the column expansion algorithm.

Step (5)

Expand the resulted matrix to D" $(H*H)$ matrix using the row expansion algorithm.D" now is an QDS matrix w.r.t. S.

Step (6)

Using the Max -Min matching algorithm [11], we can find the switching matrices corresponding to D".

Step (7)

Convert the switching matrices resulted from the previous step to permutation matrices of entries 1's and 0's only.

Step (8)

Perform row compression algorithm to the permutation matrices resulted in step (7) by adding the entries of rows which have been expanded in row expansion algorithm in step (5).

Step (9)

Perform column compression algorithm to the matrices resulting from the previous step by adding the entries of columns which have been expanded in column expansion algorithm in step (4).

Step (10)

Remove the $(M+1)$th row and $(N+1)$th column from the switching matrices to obtain $(M * N)$ switching matrices

Step(11)

Subtract the dummy traffic, if it was added in the compelition algorithm in step (3), from the switching matrices to obtain the switching matrices of the $(M* N)$ D' matrix.

Step (12)
Obtain the corresponding feasible schedule for the original matrix D by associating on a one-to-one basis, each unit of traffic in D between the same uplink beams taking into account that any switching matrix must not contain on rows which correspond to interfering uplink zones or on columns which correspond to interfering downlink zones.

Example:
Consider SS/TDMA system with 4 uplinks beams, and 3 downlinks beams, 4 transponder. The downlink beamwidth and uplink beamwidth are given by

$$\beta = (2,\ 3,\ 2)$$
$$\alpha = (2,\ 2,\ 2,\ 1)$$
$$S = 5 \qquad K = 4$$

and the uplink interference graphs is

$G_{\underline{U}}$ = 1 2 3 4 2nd and 3rd beams interefere in the uplink transmission, similarly, the downlink interference graph is

$G_{\underline{D}}$ = 1 2 3

The traffic matrix D

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

1- Add rows 2, 3 $\alpha\underline{2}$ = 2+2
2- Add columns 2, $\overline{3}$ $\beta\underline{2}$ = 3+2
3- $H = \Sigma\beta\underline{j} = \Sigma_{\alpha}\underline{i} = 7$
4- Permutation matrices

$$\begin{bmatrix} 0&0&1&0&0&0&0 \\ 0&0&0&1&0&0&0 \\ 1&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0 \\ 0&0&0&0&1&0&0 \\ 0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&1 \end{bmatrix} \quad \begin{bmatrix} 0&0&1&0&0&0&0 \\ 0&0&0&1&0&0&0 \\ 1&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0 \\ 0&0&0&0&1&0&0 \\ 0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&1 \end{bmatrix}$$

$$\begin{bmatrix} 0&0&1&0&0&0&0 \\ 0&0&1&0&0&0&0 \\ 1&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0 \\ 0&0&0&0&1&0&0 \\ 0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&1 \end{bmatrix} \quad \begin{bmatrix} 1&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0 \\ 0&1&0&0&0&0&0 \\ 0&0&0&1&0&0&0 \\ 0&0&0&0&1&0&0 \\ 0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&1 \end{bmatrix}$$

$$\begin{bmatrix} 1&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0 \\ 0&1&0&0&0&0&0 \\ 0&0&0&1&0&0&0 \\ 0&0&0&0&1&0&0 \\ 0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&1 \end{bmatrix}$$

5- Row compression (1+2), (3+4+5+6), (7)

$$\begin{bmatrix} 0&0&1&1&0&0&0 \\ 1&1&0&0&1&1&0 \\ 0&0&0&0&0&0&1 \end{bmatrix} \quad \begin{bmatrix} 0&0&1&1&0&0&0 \\ 1&1&0&0&1&1&0 \\ 0&0&0&0&0&0&1 \end{bmatrix}$$

$$\begin{bmatrix} 1&0&1&0&0&0&0 \\ 0&1&0&1&1&1&0 \\ 0&0&0&0&0&0&1 \end{bmatrix} \quad \begin{bmatrix} 1&0&1&0&0&0&0 \\ 0&1&0&1&1&1&0 \\ 0&0&0&0&0&0&1 \end{bmatrix}$$

$$\begin{bmatrix} 1&0&1&0&0&0&0 \\ 0&1&0&1&1&1&0 \\ 0&0&0&0&0&0&1 \end{bmatrix}$$

6- Column compression (1+2), (3+4+5+6,7)

$$\begin{bmatrix} 0&2 \\ 2&2 \\ 0&1 \end{bmatrix} \quad \begin{bmatrix} 0&2 \\ 2&2 \\ 0&1 \end{bmatrix} \quad \begin{bmatrix} 0&2 \\ 2&2 \\ 0&1 \end{bmatrix} \quad \begin{bmatrix} 1&1 \\ 1&3 \\ 0&1 \end{bmatrix} \quad \begin{bmatrix} 1&1 \\ 1&3 \\ 0&1 \end{bmatrix}$$

7- The corresponding matrices of D are

$$\underset{\text{Type1}}{\begin{bmatrix} 0&1&0 \\ 1&1&0 \\ 0&0&0 \\ 0&1&0 \end{bmatrix}} \quad \underset{\text{Type2}}{\begin{bmatrix} 0&0&1 \\ 0&0&0 \\ 1&0&1 \\ 0&0&0 \end{bmatrix}} \quad \underset{\text{Type3}}{\begin{bmatrix} 1&1&0 \\ 0&1&0 \\ 0&0&0 \\ 0&1&0 \end{bmatrix}} \quad \underset{\text{Type4}}{\begin{bmatrix} 0&0&0 \\ 0&0&0 \\ 1&0&1 \\ 0&0&0 \end{bmatrix}} \quad \underset{\text{Type5}}{\begin{bmatrix} 0&0&0 \\ 0&0&1 \\ 0&0&0 \\ 0&0&0 \end{bmatrix}}$$

There are 3 matrices of the first type, 3 of the second, 2 of the third, 2 of the forth, and 2 of the fifth one. The total duration is 12

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