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New bounds for optium traffic assignment in satellite communication

by

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NEW BOUNDS FOR OPTIMUM TRAFFIC ASSIGNMENT IN SATELLITE COMMUNICATION

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Scope and Purpose–The use of satellites to exchange information between distant places on the earth is a well assessed technique, but each satellite has an high cost, so it is important to utilize it efficiently. A satellite receives requests of transmission between pairs of earth stations, which can be represented by a *traffic matrix*. One of the methods used for managing these communications is the the Satellite Switched Time-Division-Multiple-Access system which requires to partition the traffic matrix in submatrices and transmits the information of each submatrix in a single time slot. Therefore a crucial decision for an efficient use of the satellite is how to partition the given traffic matrix so that the total time required to transmit the information is minimized. In the literature this problem has been addressed only in the special case in which the number of possible contemporary transmissions is equal to the number of rows and columns in the traffic matrix. In this paper we consider the general case in which the size of the matrix is larger than the number of contemporary transmissions. Our scope is to provide effective heuristic algorithms for finding good approximating solutions and to give tight lower bounds on the optimal solution value, in order to evaluate the quality of the heuristics.

Abstract– In this paper we assume that a satellite has ℓ receiving and transmitting antennas, and we are given a traffic matrix D to be transmitted by interconnecting pairs of receiving-transmitting antennas, through an on board switch. We also assume that ℓ is strictly smaller than the number of rows and columns of D, that no preemption of the communications is allowed, and that changing the configuration of the switch requires a negligible time. We ask for a set of switch configurations that minimizes the total time occurring for transmitting the entire traffic matrix. We present some new lower bounds on the optimum solution value and a new technique to combine bounds which obtains a dominating value. We then present five heuristics: the first two are obtained modifying algorithms from the literature; two others are obtained with standard techniques; the last algorithm is an implementation of a new and promising tabu search method which is called *Exploring tabu Search*. Extensive computational experiments compare the performances of the heuristics and that of the lower bound, on randomly generated instances.

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1. INTRODUCTION

A very common system in use in order to utilize efficiently a geostationary satellite for communications is known as Satellite-Switched Time-Division-Multiple-Access ($SS/TDMA$) system [17, 1]. In such a system the satellite has a number of spot beam antennas covering geographically distributed zones and an on-board switch to connect receiving and transmitting antennas. We assume that there are n receiving and n transmitting antennas on the ground, and that at most ℓ ($\ell \leq n$) simultaneous connections can be established through the satellite. Each group of simultaneous connections, in which each antenna is connected to at most another antenna, is called a *switching mode.*

We are interested into the problem of the most efficient transmission of a given *traffic matrix* in such a system. A traffic matrix is a matrix D whose entries d_{ij} define a connection duration between a receiving antenna i and a transmitting antenna j. In this model we assume that the switching time required to change the configuration of the on-board switch is significantly smaller than the minimum d_{ij}. We further assume that once two antennas i and j are connected, they can not be disconnected before d_{ij} time units, viz. no preemption is allowed. The objective is to determine a sequence of switching modes ensuring that the whole traffic is transmitted through the satellite in the minimum possible time.

The problem has been studied since the middle 70's [19] and several heuristics have appeared in the literature [11, 3, 2]. The particular case of $\ell = n$ has been shown NP-hard in [16]. Exact solution algorithms have been quite rare [18]. Some extensions have also been analyzed allowing for more than one transmitting antenna to be connected to the same receiving antenna, or considering clusters of satellites [8]. Related combinatorial optimization areas are constituted by open-shop scheduling and edge-colouring problems [9, 10].

In Section 2 we give a mathematical model of the problem and we survey its complexity status. In Section 3 we present some new lower bounds and compare them with those already available in the literature. In Section 4 we present some heuristic methods to obtain upper bounds to the problem. Section 5 contains the experimental results obtained by comparing the heuristic algorithms.

2. MATHEMATICAL MODEL

Given an $n \times n$ traffic matrix D with $m \leq n^2$ positive integer entries and a positive integer $\ell \leq n$ the $SS/TDMA$ problem we consider is to decompose matrix D into a number of $n \times n$ *switching* matrices $D_1, D_2, \ldots, D_q$ such that:

(i) at most one entry in each row or column of $D_k = [d_{ij}^k]$ $(k = 1, \ldots, q)$ is greater than zero;

(ii) at most ℓ entries in each matrix D_k $(k = 1, \ldots, q)$ are greater than zero;

(iii) for each entry $d_{ij} > 0$ in D there exists one matrix D_k with entry $d_{ij}^k = d_{ij}$;

(iv) $z = \sum_{k=1}^{q} max_{ij}\{d_{ij}^k\}$ is minimized.

Observe that due to the constraints (i) and (iii) it is $\sum_{k=1}^{q} D_k = D$. Moreover (iii) implies that no preemption of the entries of D is allowed and the decomposition is indeed a partition of the positive entries of D into q sets $S_1, \ldots, S_q$, such that $|S_k| \leq \ell$, and no two elements of S_k belong to the same row or column of D, for $k = 1, \ldots, q$.

Each set S_k determines a *switching mode* and is assigned to a *frame* of transmission.

The value of q can be set to any upper bound on the number of frames required by the optimal solution, indeed empty matrices are allowed. In particular one can set $q = m$

In the remaining of the paper we will refer to the above problem as problem P, for short. We define the binary variables

$$x_{ij}^k = \begin{cases} 1 & \text{if } d_{ij} \text{ is transmitted in frame } k, \\ 0 & \text{otherwise.} \end{cases}$$

Problem P can be modeled as a Mixed Integer Problem, as follows:

$$
\begin{aligned}
P: \quad \min z(P) &= \sum_{k=1}^{q} z_k && (1)\\
\text{s.t.} & && \\
d_{ij} x_{ij}^k &\leq z_k \quad i,j = 1,\ldots,n;\ k = 1,\ldots,q, && (2)\\
\sum_{i=1}^{n} x_{ij}^k &\leq 1 \quad j = 1,\ldots,n;\ k = 1,\ldots,q, && (3)\\
\sum_{j=1}^{n} x_{ij}^k &\leq 1 \quad i = 1,\ldots,n;\ k = 1,\ldots,q, && (4)\\
\sum_{i=1}^{n}\sum_{j=1}^{n} x_{ij}^k &\leq \ell \quad k = 1,\ldots,q, && (5)\\
\sum_{k=1}^{q} x_{ij}^k &= 1 \quad i,j = 1,\ldots,n, && (6)\\
x_{ij}^k &\in \{0,1\} \quad i,j = 1,\ldots,n;\ k = 1,\ldots,q. && (7)
\end{aligned}
$$

Without loss of generality we will consider only optimal solutions such that

$$z_i \geq z_{i+1} \quad i = 1,\ldots,q-1. \qquad (8)$$

In [16] it is proved that the *Latin Square Decomposition* problem (LSD) is NP_hard. LSD can be obtained from P considering the particular instances with $m = n^2$ and $\ell = n$, and adding the constraint that the number of matrices in the decomposition must be equal to n. Given an instance of LSD it can be polynomially transformed to an instance of P simply adding a large positive constant value to each entry of D and setting $\ell = n$. It is clear that any optimal solution to this instance of P has exactly n switching matrices, so it is also an optimal solution to LSD.

3. LOWER BOUNDS

In this section we present the lower bound proposed for problem P in the literature, then we introduce new bounds from constraints relaxation and finally we show how to combine these bounds to obtain a better estimate of the optimal objective function value. When no ambiguity arise we will use the same symbol, (e.g. $L01$) to identify both a procedure which determine a lower bound and the value obtained by means of this procedure.

The following simple lower bound are known (see e.g. [14]):

$$L01 = \max(\left\lceil \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} d_{ij}}{\ell} \right\rceil), \tag{9}$$

$$L02 = \max(\max_{i=1,\dots,n} \sum_{j=1}^{n} d_{ij}, \max_{j=1,\dots,n} \sum_{i=1}^{n} d_{ij}). \tag{10}$$

$L01$ exploits the fact that the total traffic of matrix D has to be transmitted using ℓ channels. $L02$ considers the constraints that impose to transmit the traffic of a same row or column in intervals of time which does not overlap. An overall lower bound is $L0 = \max(L01, L02)$.

3.1. *Lower bounds from constraints removal*

We introduce new lower bounds based on the relaxation of constraints of problem P. In particular we address the three characterizing constraints (3)–(5) and we consider the relaxed problems obtained by removing two of these constraints.

Lower Bound L1

Consider the relaxed problem P^ℓ obtained from P by removing constraints (3) and (4). Problem P^ℓ asks for a minimum cost partition of the entries of D, such that each set of the partition has cardinality not greater than ℓ. Our first lower bound is $L1 = \min z(P^\ell)$.

The problem can be easily solved ordering the entries of D by nonincreasing d_{ij} values and by assigning the first ℓ entries to the first set, the entries from the $(\ell + 1)-$th to the (2ℓ)-th to the second frame and so on. One could prove the optimality of this solution by a simple exchange argument. The value $L1$ is given by

$$L1 = \max[1](D) + \max[\ell + 1](D) + \ldots + \max[\lfloor m/\ell \rfloor \ell + 1](D) \tag{11}$$

where $\max[h](D)$ denotes the h-th element of matrix D, in nonincreasing order.

Theorem 1. *Lower bound $L1$ dominates bound $L01$.*

Proof. the lower bounding procedure $L01$ implicitly considers the particular preemptive relaxation $\hat{P}$ of P, obtained adopting only the two following constraints: (a) all the information in each entry of D must be transmitted; and (b) no more than ℓ transmissions can be active at the same time instant.

Given a traffic matrix D and an optimal solution of problem P^ℓ, for this matrix, we can always transform this solution into a solution of problem $\hat{P}$ such that $z(\hat{P}) \leq z(P^\ell) = L1$, thus proving the thesis.

Consider the k-th switch matrix in the solution of P^ℓ and let Σ and μ be, respectively, the sum of the values of all the entries of D assigned to frame k, and the maximum of these values. In frame k there are exactly $\ell \times \mu - \Sigma$ unused time units. If we fill the frame by moving elements (or part of elements) from the last frame to the unused time, we obtain a solution which is not feasible for P^ℓ, but it is for $\hat{P}$ and $z(\hat{P}) \le z(P^\ell)$, as required. ∎

The two following examples help to study the relations between lower bounds $L1$ and $L0$.

Example 1. Consider the transmission matrix $D = \begin{bmatrix} 10 & 4 & 3 & 2 \\ 4 & 10 & 2 & 3 \\ 2 & 3 & 10 & 4 \\ 1 & 2 & 1 & 10 \end{bmatrix}$, and assume $\ell = 3$. It is $\left\lceil \sum_{i=1}^{n} \sum_{j=1}^{n} d_{ij}/\ell \right\rceil = \lceil 71/3 \rceil$, so $L01 = 24$. Using (10) we obtain $L02 = \sum_{j=1}^{n} d_{1j} = 19$, and finally using (11) we have $L1 = 10 + 10 + 4 + 3 + 2 + 1 = 30$, thus $L1 > L01 > L02$.

Example 2. Let $D = \begin{bmatrix} 10 & 4 & 2 & 1 \\ 10 & 3 & 2 & 1 \\ 10 & 3 & 1 & 1 \\ 1 & 2 & 1 & 1 \end{bmatrix}$, and $\ell = 3$. Applying again (9), (10) and (11) we have, respectively, $L01 = \lceil 53/3 \rceil = 18$, $L02 = \sum_{i=1}^{n} d_{i1} = 31$ and $L1 = 10+4+2+1+1+1 = 19$, thus $L02 > L1 > L01$.

From the above examples it immediately descends that lower bounds $L02$ and $L1$ do not dominates one each other, so the following holds.

Theorem 2. *Lower bounds $L0$ and $L1$ do not dominate.*

Lower Bound L2

Consider the relaxed problem P^c obtained from P by removing constraints (4) and (5), i.e. by maintaining only the column constraints, among the three characterizing constraints (3)–(5). Problem P^c asks for a minimum cost partition of the entries of D such that no two elements assigned to the same set of the partition belongs to the same column of D. Similarly we obtain problem P^r by removing constraints (3) and (5), i.e. by maintaining the row constraints.

We define $L2^c = \min z(P^c)$, $L2^r = \min z(P^r)$ and the overall lower bound $L2 = \max(L2^c, L2^r)$.

Problem P^c can be solved as follows. We start by defining a matrix D' obtained from D by reordering each column j in such a way that $d'_{ij} \ge d'_{i+1,j}$ $(i = 1, \dots, n-1)$. Then we define a solution of P^c by assigning to each frame k, for $k = 1, 2, \dots$, the positive entries of the k-th row of D'. It is immediate to see that this solution is feasible for P^c. Moreover one can use an exchange argument to prove that the solution is optimal (observe that no more than one element from a given column can be assigned to the same frame and that the proposed solution assigns the k-th largest entry of each column to the k-th frame). The optimal solution value is:

$$L2^c = \sum_{i=1}^{n} \max_{j=1,\dots,n} d'_{ij} = \sum_{i=1}^{n} \max_{j=1,\dots,n} \max[i](d_{1j}, \dots, d_{nj}). \tag{12}$$

Problem P^r can be solved with a similar method, by defining a matrix D'' obtained from D by reordering each row so that $d''_{ij} \ge d''_{i,j+1}$, and assigning to each frame k, for $k = 1, \dots, n$

the n entries of the k-th column of D''. Thus we obtain

$$L2^r = \sum_{j=1}^{n} \max_{i=1,\dots,n} d''_{ij} = \sum_{j=1}^{n} \max_{i=1,\dots,n} \max[j](d_{i1},\dots,d_{in}). \tag{13}$$

Example 1 (continued). The matrices D' and D'' used by lower bound $L2$ are:

$$D' = \begin{bmatrix} 10 & 10 & 10 & 10 \\ 4 & 4 & 3 & 4 \\ 2 & 3 & 2 & 3 \\ 1 & 2 & 1 & 2 \end{bmatrix}, \quad D'' = \begin{bmatrix} 10 & 4 & 3 & 2 \\ 10 & 4 & 3 & 2 \\ 10 & 4 & 3 & 2 \\ 10 & 2 & 1 & 1 \end{bmatrix},$$

so it follows $L2^c = 10+4+3+2 = 19$ and $L2^r = 10+4+3+2 = 19$. We have already computed $L0 = L01 = 24$ and $L1 = 30$, thus $L2 < L0$ and $L2 < L1$. (However note that $L2 = L02 = 19$, indeed we will show that $L2$ is always not worse than $L02$.)

Example 2 (continued). In this case we have $L2^c = 32$ and $L2^r = 17$, so $L2 > L1 = 19$ and $L2 > L0 = L02 = 31$.

The above examples show that no one of the three lower bounds $L0$, $L1$ and $L2$ dominates any one of the others. However we can establish a dominance relation from $\max(L1, L2)$ to $L0$. To do this we need the following

Theorem 3. *Lower bound $L2$ dominates bound $L02$.*

Proof. let ρ be the index of the column which produces the lower bound value $L02$. i.e. $L02 = \sum_{i=1}^{n} d_{i\rho}$. Since matrix D' is matrix D with the elements of a same column reordered, it is also $L02 = \sum_{i=1}^{n} d'_{i\rho}$, but for each row i the bound $L2$ selects the value $\max_{j=1,\dots,n} d'_{ij} \geq d'_{i\rho}$ (see (12)), so the thesis holds. ∎

From Theorems 2 and 3 the claimed relation immediately descends.

Theorem 4. $\max(L1, L2) \geq L0$.

3.2. *Combining the Bounds*

In this section we introduce a method which allows to combine the lower bounds presented above and to obtain new better bounds.

Observe that if we are able to compute a lower bound LB_k on the maximum weight of an element in the k-th frame of any optimal solution, then an overall lower bound can be obtained as:

$$LB = \sum_{k=1}^{q} LB_k. \tag{14}$$

Moreover if we know several *techniques* to obtain the bound for the k-th frame, we can even increase the value LB by selecting the maximum value, for each frame, among those produced by the different techniques. More formally let $LB_k(\tau)$ be the lower bound value for the k-th frame, when computed with technique τ, and let $\mathcal{T}$ denote the set of all the known techniques. Then a new lower bound can be computed as:

$$LB = \sum_{k=1}^{q} \max_{\tau \in \mathcal{T}} LB_k(\tau). \quad (15)$$

The main result of this section is that the lower bounds developed in the previous Section 3 for the entire problem, can be adapted to produce a valid lower bound for a single frame.

Let us define a *ranking relationship* between two partition problems.

Definition 1. Let $E = \{e_1, \ldots, e_m\}$ be a finite set of integer numbers and let $\mathcal{P}$ be the set of all the proper partitions of E. Moreover let P^a and P^b be two partitioning problems whose feasible solution sets are subsets of E. Given the optimal solution $S^a = (S^a_1, S^a_2, \ldots, S^a_{qa})$, for P^a, and the optimal solution $S^b = (S^b_1, S^b_2, \ldots, S^b_{qb})$, for P^b, we say that P^a is in a *ranking relationship* with P^b, if $qa \geq qb$ and $\max\{e_i : e_i \in S^a_k\} \geq \max\{e_i : e_i \in S^b_k\}$, for $k = 1, \ldots, qb$. The ranking relationship will be denoted with the symbol $\succ$.

From the above definition it is clear that if $P^a \succ P^b$, and if P^b is easier to be solved than P^a, then we can assume the value of the k-th frame in the solution of P^b, as a lower bound on the value of the k-th frame in the optimal solution to P^a.

Theorem 5. *Problem P is in a ranking relationship with problem P^ℓ, with problem P^c and with problem P^r.*

Proof. let $S = (S_1, S_2, \ldots, S_q)$ be the optimal solution of problem P, ordered according to (8). Note that due to the cardinality constraint (5), q (the number of frames in S) is certainly not smaller than $\lceil m/\ell \rceil$ (the number of frames in any optimal solution to P^ℓ). Moreover, if we denote with $\bar{c}$ and $\bar{r}$ the maximum number of positive entries in a column and in a row of D, respectively, then one can see that the number of frames in an optimal solution to P^c and P^r is exactly $\bar{c}$ and $\bar{r}$, respectively, and $q \geq \max(\bar{c}, \bar{r})$. Thus $q \geq \max(\lceil m/\ell \rceil, \bar{c}, \bar{r})$ and the first requirement of Definition 1 holds.

Given a frame index $k \in \{1, \ldots, q\}$ the largest value in S_k, cannot be smaller than

(a) the value of the $((k-1)\ell + 1)$-th largest element of D (i.e. $\max[(k-1)\ell + 1](D)$, see (11)), because of the cardinality constraint (5);

(b) the maximum of the columns' k-th largest element (i.e. $\max_{j=1,\ldots,n} \max[k](d_{1j}, \ldots, d_{nj})$ see (12)), because of the column constraints (3);

(c) the maximum of the rows' k-th largest element (i.e. $\max_{i=1,\ldots,n} \max[k](d_{i1}, \ldots, d_{in})$ see (13)), because of the row constraints (4).

But the values of points (a), (b) and (c) are, respectively, the value of the largest element assigned to the k-th frame in the solutions of problem P^ℓ, P^a and P^b, so also the second requirement of Definition 1 holds and the thesis follows. ■

Let $\phi = \max(\lceil m/\ell \rceil, n)$ and let $LB_k(L1)$, $LB_k(L2^c)$ and $LB_k(L2^r)$, for $k = 1, \ldots, \phi$, be the maximum weight of an element in the k-th frame of the optimal solution to problem P^ℓ, P^a and P^b, respectively (if the solution obtained with a lower bounding technique x has $\nu < \phi$ frames, then let $LB_k(x) = 0$ for $k = \nu + 1, \ldots, \phi$). As a consequence of the above theorem, each of the three values $LB_k(L1)$, $LB_k(L2^c)$ and $LB_k(L2^r)$ is a valid lower bound on the weight of the maximum element in the k-th frame of the optimal solution to P. Thus, according to (15), we can obtain the improved lower bound

$$\widehat{LB} = \sum_{k=1}^{\phi} \max(LB_k(L1), LB_k(L2^c), LB_k(L2^r)) \tag{16}$$

The above results immediately give the following

Theorem 6. *Lower bound $\widehat{LB}$ dominates lower bounds $L0$, $L1$ and $L2$.*

4. UPPER BOUNDS

In this section we present five different approaches to determine an approximating solution to $SS/TDMA$. The performances of the corresponding algorithms are analyzed, through extensive computational experiments, in the next section. The first two algorithms have been obtained by modifying two algorithms proposed for the case $\ell = n$ (see [3] and [2]). The third approach is a *multi-start* algorithm based on a greedy constructive procedure, the fourth is a *local search* algorithm and the last one is an implementation of the *Exploring Tabu Search* proposed in [4].

4.1. *Algorithms based on matching problems*

In the literature the $SS/TDMA$ has been mainly considered in the case $\ell = n$, $m = n^2$ and $q = n$ (i.e. the special case asking for a decomposition of a full $n \times n$ traffic matrix into n submatrices). Two heuristic algorithms have been introduced in [3] and [2], both of them being based on the observation that the elements of D assigned to a frame of transmission define a matching on the bipartite graph $G = (S \cup T, E)$ obtained by associating one vertex $i \in S$ to each row of D, one vertex $j \in T$ to each column, and one edge $(i, j) \in E$ to each positive entry d_{ij}. When all the entries of D are positive, then G can be decomposed into n complete matching (i.e. matchings of cardinality n). The two algorithms adopt the same general scheme, but differ in the method used to find a matching. The outline of the algorithms is the following:

Procedure $match(n, D, S^*)$
input: an $n \times n$ traffic matrix D;
output: the partition $S^* = (S_1^*, \ldots, S_q^*)$;
define the graph G associated with matrix D, set $q := 1$;
while $(E \neq \emptyset)$ **do**
    determine a complete matching M of G, which optimizes a given objective function;
    set $E := E \backslash M$, $q := q + 1$;
    put the elements of D associated to the elements of M in the q-th frame S_q^*
endwhile

In [3] the authors propose to find, at each iteration, the complete matching which minimizes the sum of the elements chosen. To determine these matchings a *linear assignment* problem (AP) on D is solved, by means of an Hungarian algorithm (see e.g. [6] for an updated bibliography on such algorithms). The idea developed in [2], instead, is to find a *bottleneck* matching, i.e. a complete matching minimizing the maximum weight of an edge in the solution. A threshold algorithm (see e.g. [13]) has been used by the authors to determine these matchings. The computational results reported in [2] show that the bottleneck approach is superior to the min-sum approach of [3].

We adapted the two above algorithms to the case $\ell < n$. For the min-sum approach of [3] it was sufficient to substitute the algorithm for the solution of AP, with the procedure for the solution of the *cardinality-constrained assignment problem* developed in [5]. For the bottleneck approach, instead, we implemented the threshold method as described in [2]. This method defines a threshold value θ with a bisection technique, and, for each θ value, a labeling technique is used to find a maximum cardinality matching in the subgraph defined by the edges with weight smaller or equal to θ. We modified the stopping criterion in the labeling phase, so that the matching is considered complete when ℓ edges have been chosen.

A first set of computational experiments showed that these algorithms produce very bad solutions. This is due to the fact that the idea of minimizing the weight of the matchings (either in the min-sum or in the bottleneck version) is not the right one when $\ell < n$. Indeed, with this approach the lightest elements are assigned to the first frames and the heaviest to the last ones. But in the problems studied in [3] and [2] the number of frames in a solution is fixed, so that it does not matter whether the heaviest frames are the last or the first ones. Instead with problem P the number of frames in a solution depends on the selections made (and on the column and row constraints). So if we leave the heaviest elements to be assigned late, in general, they are assigned to different frames, thus giving a high value of the objective function. To overcome this problem we reversed the criterion used in the above algorithms, thus obtaining two new algorithms which select the matching which maximize, respectively, the total sum of the edges, or the weight of the bottleneck element. With this approach the heaviest elements are packed in the first (few) frames and the objective function value is small. The computational experiments showed that this approach is definitely better than the original methods of [3] and [2].

4.2. *The multi-start algorithm*

We have implemented a greedy method similar to the *First-Fit* (FF) algorithm developed for the *Bin Packing Problem* (BPP). With BPP we are given m items with weight w_i, for $i = 1, \dots, m$, and an infinite number of bins of equal capacity C. The problem is to assign the items to the bins, in such a way that the sum of the weights of the elements assigned to the same bin does not exceed C, and the number of bins used is minimized. Given a *list* L containing all the items, then algorithm FF assigns an item at a time from L, to the first bin in which it fits. Several greedy algorithms can be obtained by defining different ordering of the items in L. If the list is ordered by nonincreasing w_i values the algorithm is called *First-Fit Decreasing* (FFD).

We adopted a similar method which sorts the elements of matrix D by nonincreasing d_{ij} values and assigns an element at a time, to the first frame in which it can be placed, without violating the column, row and cardinality constraints (3)–(5).

To improve this method we introduced a randomization in the construction of the solution. At each step of the greedy algorithm we randomly select one of the first three elements in the ranking given by the nonincreasing order. Due to this randomization, different executions of the algorithm produce different solutions. So the final *multi-start* procedure is obtained by running the randomized greedy until a given time limit is reached, and returning the best solution generated.

4.3. *Algorithms based on local search*

We developed two algorithms based on local search: the first is a pure local search algorithm, whilst the second uses advanced techniques to take advantages from the history of the search, as for the recently introduced Exploring Tabu Search metaheuristic (see [4,7]). Both methods need a procedure to determine feasible solutions and a neighborhood structure, i.e. a relationship which associates each feasible solution S with a set of feasible solutions $\mathcal{N}(S)$. The transformation from S to a solution $S' \in \mathcal{N}(s)$ is usually given by a simple modification of S, called *move.*

4.3.1 *Basic local search*

In our problem P the possible modifications to a feasible solution S are strongly conditioned by the three main constraints (3)–(5), thus a simple move generally leads to an unfeasible configuration and more complicate moves are necessary to transform S into a new feasible solution. Indeed any simple transformation of the solution (e.g. moving one element from a frame to another, or exchanging two elements belonging to different frames), immediately generates a water fall effect: many other transformations are necessary to re-establish the feasibility of the solution. Moreover, given an initial simple move, there are several sets of transformations leading to feasible solutions, and the analysis of the neighborhood could be computationally very expensive.

We have overcome these difficulties using the following observation, whose proof can be easily obtained.

Observation 1. *Any given solution to* $SS/TDMA$ *can be generated applying algorithm* FF *initialized with an appropriate list of the nonnegative elements of matrix* D.

Thus we have devised a neighborhood structure based on moves within the set of all the possible lists, i.e. the *permutations* of the nonnegative elements of D. Given a solution S obtained using algorithm FF, initialized with a list L, we transform the list with simple moves like *shifting* an element or *exchanging* two elements: the modified list, say L', is used to obtain the new solution S', applying again algorithm FF. (A similar approach has been used, e.g., in [15] in the context of a *genetic algorithm* for the solution of the Flow Shop scheduling problem.)

However there is still a strong drawback with this approach: a number of different permutations produce the same solution. As a consequence there could be a large waste of computational time, computing unfruitful lists and schedules, associated to already examined solutions. (To see that more permutations can be associated to the same schedule it is enough to consider a solution $S = (S_1, \ldots, S_q)$ and define a list L putting in the first $|S_1|$ positions the elements assigned to S_1, then the elements assigned to S_2, etc. One can see that FF applied with list L produces S, but FF applied with any list L' obtained from L by permuting the elements associated to the same frame, also produce the same solution S.)

More structured moves are then necessary to avoid to consider more than once the same solution in the exploration of a neighborhood. Given a solution $S = (S_1, \ldots, S_q)$ we define a total ordering of the positive elements of D by imposing that an element (i, j) precedes an element (h, k) if the frame at which (i, j) is assigned follows the frame at which (h, k) is assigned, in the ordering given by (8), or the two elements are assigned to the same frame and $d_{ij} > d_{hk}$, or the two elements are assigned to the same frame, $d_{ij} = d_{hk}$ and $i \cdot n + j < h \cdot n + k$. This ordering uniquely defines the list L associated to the current solution. (Note that the first rule for obtaining the total ordering is opposite to the more natural rule given by (8), but with our choice we obtain a stronger differentiation among the solutions belonging to the same neighborhood.) Given a couple of frames S_r and S_s, with $r < s$, let (i, j) and (h, k) denote the heaviest elements in S_r and S_s respectively, and observe that $d_{ij} \leq d_{hk}$. If (i, j) and (h, k) could be assigned to the same frame (i.e. if $i \neq h$ and $j \neq k$), then we generate a neighbor of S by driving FF with a list L' obtained by moving (i, j) immediately after (h, k), in the list L. The basic idea with this neighborhood is that an improvement of the current solution value could be obtained only if the heaviest element of a frame is removed and assigned to a different frame whose heaviest element is not smaller than the moved one.

The whole neighborhood $\mathcal{N}(S)$ is obtained by repeating the above move for $r = q - 1$, down to 1, and $s = q$, down to $r + 1$. Thus the cardinality of $\mathcal{N}(S)$ is $O(q^2)$ and a full exploration requires $O(q^3 m)$, since FF runs in $O(qm)$. To speed up the search, we decided to implement an algorithm which explores $\mathcal{N}(S)$ not looking for the *best* solution, as usually done, but for the *first* improving solution. The complete local search algorithm is as follows:

Proceduere $LS(n, D, \ell, q, S^s, z^*)$
input: an $n \times n$ traffic matrix D, a cardinality ℓ;
output: the solution $S^* = (S_1^*, \ldots, S_q^*)$ with value z^*;
Let $z^* := \infty, S^* := \emptyset$;
while (a given time limit is not reached) **do**
    generate a starting solution S;
    repeat
        if $z(S) < z^*$ **then** $z^* := z(S),\ S^* := S$;
        find the first improving solution $S' \in \mathcal{N}(S)$;
        if $(S' \neq \emptyset)$ **then** $S := S'$;
    until $(S' = \emptyset)$
endwhile

Algorithm LS repeats the search of a local minimum, starting from different solutions, until it not reaches the maximum computational time given to it. The first initial solution is generated by algorithm FFD, the other solutions are obtained by randomly generating a permutation of $\{1, 2, \ldots, m\}$ and applying FF to the resulting list.

4.3.2 *The Exploring Tabu Search*

The last algorithm tested is an implementation of the Exploring Tabu Search ($\mathcal{X}$-TS) proposed in [4] which has been already applied with success to other combinatorial problems, see [7]. Before presenting the main characteristics of this method we need to describe how we modify neighborhood $\mathcal{N}(S)$, so that it can be used in the contest of a tabu search algorithm. Indeed, even the variant of $\mathcal{N}(S)$ which only looks for the first improving solution, is computationally too heavy for being used in a framework which usually needs frequent evaluations of the neighborhood. Therefore we defined a new version $\mathcal{RN}(S)$ of $\mathcal{N}(S)$ which contains only feasible solutions that can be generated without using algorithm FF. More specifically the solutions in $\mathcal{RN}(S)$ are generated using only four kinds of moves which ensure the immediate feasibility of the new solutions. Each move starts removing (i, j), the heaviest element of frame S_r, as done in $\mathcal{N}(S)$, and terminates as follows:

move 1: (i, j) is assigned to an already initialized frame, if no constraint is violated with this assignment;

move 2: (i, j) is moved to a frame S_s and an element $(h, k) \in S_s$ is moved to S_r, if no constraint is violated by the new solution;

move 3: (i, j) is assigned to a frame S_s and an element (h, k) is removed from S_s and assigned to a new frame, if the resulting solution is feasible;

move 4: a new frame is created and (i, j) is assigned to it.

The whole neighborhood $\mathcal{RN}(S)$ is obtained by choosing the initial element (i, j) from each "source" frame and trying to assign it to all the other "destination" frames. Given a pair of source-destination frames all the moves, but the second one, can be evaluated in constant time. The analysis of move 2 requires $O(\ell)$ time when only the cardinality constraint (5) is violated by inserting (i, j) in the destination frame, otherwise (a column or row constraint is violated) the analysis of this move too can be done in $O(1)$. Therefore a full exploration of $\mathcal{RN}(S)$ requires at most $O(q^2\ell)$ time. Due to the reduced computational complexity $\mathcal{RN}(S)$ is explored completely in order to identify the best neighbor and not the first improving neighbor, as done for $\mathcal{N}(S)$.

In the following we assume that the reader is familiar with the main concepts of the Tabu Search (TS) metaheuristic (see e.g. [12)], and we only describe the characteristics of the $\mathcal{X}$-TS approach and of our implementation. The general elements which define a tabu search-based algorithm are: *memory structures*, which capture relevant information during the search process, and *strategies* which define how to use this information in the best possible way. With the $\mathcal{X}$-TS method the structures and strategies are as follows:

(i) a dynamic updating of the length of the tabu list is used as a first-level tool for intensifying the search when we suppose to be close to a local minimum, and for a fast escaping from already visited solutions;

(ii) a long term memory based on the memorization of "good" solutions, is used to drive the search into promising regions, considered during the search, but not yet visited; this is a second-level tool for intensifying the search into regions analyzed, but not completely explored, and for diversifying the search from the current local optimum;

(iii) a global restarting technique, which uses an "intelligent" procedure for randomly generating feasible solutions, is used as a third-level tool which allow an immediate jump into new regions, so giving a strong diversification;

(iv) an aspiration criterion based on the memorization of few recent solutions is sometime applied to overcome heavy constraints due to the tabu restrictions.

Dynamic updating of the tabu list

A tabu list, or *short term memory*, is used to record *attributes* of those solutions recently generated in the evolution of the search. The attributes we associate to a solution are the elements that have been assigned to different frames to obtain the current solution from the previous one. More precisely, if the current solution is generated according to move 1 or 4, then the removed element (i, j) is the only stored attribute, otherwise both the elements (i, j) and (h, k) are put in the short term memory. For a number of iterations all the moves proposing the removal of an element currently in the tabu list are forbidden. The tabu tenure l, i.e. the number of iterations a solution maintains its tabu status, is initialized to a value *tabu_tenure* and modified according to the evolution of the search process. The aim of decreasing l is that of *locally* intensifying the search, whilst the aim of increasing it is that of speeding up the leaving from the already visited local minima.

We call *improving phase* a set of Δip consecutive iterations which lower the objective function value, and we call *worsening phase* a set of Δwp consecutive iterations in which the objective function value does not improve. After an improving phase l is decreased by 1, if it is larger than $\frac{1}{2}tabu\_tenure$, instead after a worsening phase l is increased by 1, if it is smaller than $\frac{3}{2}tabu\_tenure$.

Preliminary computational experiments have been used to fix the value of *tabu_tenure* to 10 and the values of Δip and Δwp to 5 and 3 respectively. The same parameters have been used for all the remaining experiments, presented in Section 5.

Long term memory

A priority queue of fixed length L is used to store some of the high quality solutions which were analyzed during the search, but whose value was only the second best value in their neighborhood. This memory structure, denoted as *Second*, is updated at each exploration of a neighborhood, and it contains the L second best solutions found during the search. When one of the three following conditions holds, we remove from *Second* the solution with the best objective function value and we continue the search from that solution:

1. all the solutions in the current neighborhood are tabu and none of them satisfies an aspiration criterion;

2. for a sequence of MC consecutive moves the current objective function value does not improve;

3. for a sequence of MB consecutive moves there has been no improving of the best solution found.

In order to restart the search with the same conditions which were present when a solution was put into the list, we associate to each solution in *Second* a copy of the tabu list.

The use of restarting from a solution in *Second* has the aim of *intensifying* the search into not fully explored promising regions. On the other hand the rule of adding to *Second* at most one solution from each neighborhood plays the role of a *diversification* strategy.

For the parameters involved in the management of the long term memory structure we adopted the following values, determined with preliminary experiments: $L = 5$, $MC = 12 + \log_1 0n$ and $MB = 75 \log_1 0n$. These apparently strange settings can be motivated as follows. The value MC determines a restarting from a solution in the *Second* list when we are trying to ascend a very deep hill starting from a valley in which we have found a local minimum, or when we are exploring a flat region. In both cases the current local optimum does not change for a number of iterations. Since the solutions stored in *Second* are not too far from the current solution, (they have been found along the path leading to the current solution), it is important that we mantain the parameter MC small enough to determine a resort to a *Second* solution as soon as we suspect to be in one of the two above situations. From a set of few preliminary experiments we have seen that the value $MC = 13$ is adeguate for the $SS/TDMA$ instances we tested, but a slight grow with n is also usefull. Since the smallest matrices used in our computational experiments have ten rows and columns, we adopted the final expression $12 + \log_1 0n$. In any case there is no great difference between the behaviour obtained with the constant or the dynamic value. The value MB, instead, is adopted to detect situations in which the exploration of the current area seems to be not fruitfull to determine the global optimum. In this case we insist on with the intensification, but the new recourse to a solution in the *Second* list also draws near to the moment in which we restart form a completely new solution (see below the subsection on the global restarting). Thus the parameter MB reduces the time need to explore the region, by inducing further intensification in the current area, and also reduces the time between two diversification points. From the above reasoning we see that the value of MB must not be too small, whereas preliminary computational experiments have shown that a sublinear grow with n determine slightly better performances.

Global restarting

The effect of the previous two tools is to try to optimize the ratio between the accurancy and the rapidity of the examination of an area in the feasible solution's space. When we suppose that the current area has been analized with a sufficient detail, we try to span through different areas of the solution's space by generating a new starting solution and re-initializing the search from this new point. It is obvious that the procedure used to generate the initial solutions must define a different solution at each run. Moreover it would be very advisable if the procedure defines solutions which are "uniformly" distributed in the solution's space. In general it is not too difficult to write a procedure satisfying the first requirement, but it is much more difficult to satisfy the second one. In our implementation we used the greedy algorithm described in Section 4, which indeed gives different solutions for different runs (with large probability), but it does not garantee any uniformity in the distribution of the solutions. In our opinion the study of greedy algorithms satisfying both the above requirments will be an important research direction in the future of the metaheuristc methods.

In our implementation of $\mathcal{X}$-TS a restarting occurs when the algorithm needs to use a solution from the *Second* list, but the list is empty, or when the algorithm tries to use a solution from the *Second* list for the $(L+1)$-th time from the beginning or from the last global restart.

This third level tool is a drastic way of implementing a strong diversification strategy.

Aspiration criteria

In tabu search algorithms some *aspiration criteria* are usually introduced to override the tabu status of those moves which are supposed to lead to not already visited or promising solutions. In our implementation we adopted the basic aspiration criterion which consists of accepting a tabu move if it leads to a solution with an objective function value better than that of the best solution found so far. We do not applied the specific criterion based on recent moves, used in the framwork of $\mathcal{X}$-TS.

Implementation details

We conclude the description of our $\mathcal{X}$-TS algorithm giving some implementation's detail. In particulare we describe how to implement an effective explorations of $\mathcal{RN}(S)$, which usually does not require an explicit examination of all the solutions in the neighborhood to identify the best one.

Given a feasibe solution S and a couple of frames S_r and S_s, with $r < s$, first we evaluate the solution S', determined with move 1. Observe that if (i, j) can be inserted into S_s without violating any constraint then: (a) the values of the solutions which can be generated with move 2 or 3 cannot improve over the value of S'; (b) if moving (i, j) is currently tabu, then also the second and third kind of move, is tabu and because of (a) the aspiration criterion cannot change the tabu status. Therefore if move 1 can be applied then the solutions obtained with move 2 and 3 need not to be generated, in spite of the tabu status.

If we cannot apply move 1, then we evaluate the solutions reachable with move 2. We order the elements of S_s by nonincreasing cost and we look for the element to be removed from S_s, in this order. Then the first solution generated by a not tabu exchange cannot be improved either by choosing one of the remaining elements to be removed from S_s, nor by generating a solution by means of move 3. So if move 2 applies for an element in S_s, we have not to examine the solutions generated with the following elements of S_s or with move 3.

5. COMPUTATIONAL EXPERIMENTS

We have implemented in FORTRAN 77 the overall bound (16) of Section 3, denoted with LB in the following. We have also implemented the approximating algorithms of Section 4: the two algorithms *mod*_CMT and *mod*_BL, derived by the approaches of [3] and [2], respectively, modified as described in Section 4; the multi-start algorithm (MS) of Section 4; the pure local search algorithm (LS) of Section 4, and finally the exploring tabu search $\mathcal{X}$-TS of Section 4. The computational experiments have been performed on a personal computer with a Pentium processor with a clock at 100 Mhtz. We used the Watcom FORTRAN 77 compiler, version 10.6, running under Windows 95.

To test the algorithms we generated and solved 900 random instances in which the positive elements of the transmission matrix D have values uniformy randomly generated in [1,100]. The instances differentiate in the number of rows and columns, which was set to $10, 20, 30, 40$ or 50, in the density d of the matrix (i.e. the number of positive entries) which was set to $25, 50, 75, 90, 95$, or 100 percent of n^2, and in the strength of the cardinality constraint defined by $\ell = \lfloor 0.5n \rfloor, \lfloor 0.75n \rfloor$ or $\lfloor 0.9n \rfloor$. For each triple (n, d, ℓ) ten random instances have been generated and solved. Algorithms MS, LS and $\mathcal{X}$-TS, has been given a time limit TL, in seconds, which increases with n^2: in particular we set $TL = 10 + \frac{3}{100}n^2$. No time limit have been imposed for *mod_*CMT and *mod_*BL.

The columns of the tables corresponding to the heuristic algorithms give: (i) the average percentage error $\Delta\%$ between the solution value and the lower bound value (i.e. $\Delta\% =$ 100(upper bound value - LB) / LB); (ii) the number of times the procedure has found the best solution, among those generated by the heuristic algorithms (bst); (iii) the average CPU time required to find the best solution (Tbst). For the columns corresponding to the lower bound the value $\Delta\%$ is the average percentage error of the lower bound value, versus the smallest value obtained by all the approximating procedures. The computing time of the lower bound procedure is not given since it is very negligible (less than 0.05 seconds for any instance).

In the first three rows of Table 1 we report the total results for each ℓ value. The entries in these rows give the average on the 300 instances generated by defining ten different instances for each possible (n, d) pair. The fourth row reports the grand totals over the entire data set: 900 instances. Algorithm $\mathcal{X}$-TS dominates all other approaches both as number of best solutions found, and as quality of the solutions. Using the index 'bst' algorithm $\mathcal{X}$-TS is the winner for more than 87% of the instances (787 instances over 900), while the second best algorithm (*mod_*CMT) find the best solution only for the 6% of the cases. Moreover the average percentage error of $\mathcal{X}$-TS is about one half of the second best result, again due to *mod_*CMT. The third best algorithm is MS, if we look at the index 'bst', whilst it is *mod_*BL if we look at the percentage error. The pure local search algorithm finds less best solutions than the other algorithms and its percentage error is extemely high. Finally observe that the gap between the upper and the lower bound values is smaller when the value of ℓ is close to n.

Table **1**, averages for fixed ℓ values and grand total

	*mod_*CMT		*mod_*BL		MS		LS		$\mathcal{X}$-TS		LB
ℓ	$\Delta\%$	bst	$\Delta\%$	bst	$\Delta\%$	bst	$\Delta\%$	bst	$\Delta\%$	bst	$\Delta\%$
$50\%n$	5.53	31	6.31	10	7.74	26	52.46	2	4.21	240	4.11
$75\%n$	7.97	16	13.14	2	15.68	2	48.93	4	5.40	285	5.37
$90\%n$	7.82	8	16.96	0	23.35	0	38.07	3	2.25	262	2.22
gr.tot.	7.11	55	12.14	12	15.59	28	46.49	9	3.95	787	3.90

In Tables 2–4 we give the details of the experiments for $\ell = 50\%n, \ell = 75\%n$ and $\ell = 90\%n$, respectively. Each entry corresponds to a triple (n, d, ℓ) and reports the average over ten random instances. One can see that algorithm $\mathcal{X}$-TS finds solutions of better quality and with shorter computing times, when ℓ goes from $50\%n$ to $90\%n$. The same happens for LS, but the other algorithms have an opposite behaviour, i.e. their performance worsen when ℓ increases, both as solution's quality and computational time. The number of best solutions found by algorithms *mod_*CMT, *mod_*BL and MS drastically decreases when ℓ increases. Worth is noting that the average computiong time of *mod_*CMT and *mod_*BL is always smaller than the time limit given to MS, LS and $\mathcal{X}$-TS, but it is smaller than the time used by $\mathcal{X}$-TS to find the best solution only for $\ell = 50\%n$, or $\ell \geq 75\%n$ and $n \leq 20$ (with some exceptions).

From the above observations it follows that $\mathcal{X}$-TS is the the best method to solve $SS/TDMA$, for all the classes of instances.

6. CONCLUSIONS

We have considered the Satellite Switched Time-Division Multiple-Access problem arisig in satellite communication. A solution to this problem consists of a partition of a given traffic matrix into submatrices each of which defines the transmissions through the satellite during a time slot. The objective function is to minimize the sum of the duration of the time slots required to transmit the entire matrix. We considered the case in which the number of on-board receiving and transmitting antennas is smaller than the number of rows of the transmission matrix, and we assumed that no preemption of the communications is allowed. We have introduced new lower bounds on the optimum solution value and a new technique to combine bounds which obtains a dominating value. We have developed and tested several approximating algoritms, obtained by using completely different techniques. In particular we have introduced a new tabu search method, called Exploring Tabu Search, which has been already succesfully applied to other combinatorial problems. We have performed extensive computational experiments with randomly generated instances, to study the performances of the heuristic algorithms and the quality of the lower bound procedure. The gap between the value of the best solution obtained with the Exploring Tabu Search method and the lower bound value, results to be smaller than five percent, thus proving the effeciveness of the method.

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Table **2**, PC Pentium 100Mhtz. seconds; $\ell = \lfloor 0.5n \rfloor$, average over ten problems.

		*mod*_CMT			*mod*_BL			MS			LS			$\mathcal{X}$-TS			LB
n	d	Δ%	bst	Tbst	Δ%	bst	Tbst	Δ%	bst	Tbst	Δ%	bst	Tbst	Δ%	bst	Tbst	Δ%
	25	8.2	3	0.02	10.6	2	0.01	12.9	0	3.41	14.3	1	4.14	3.6	9	4.94	3.2
	50	8.9	0	0.09	9.9	1	0.02	9.1	1	5.43	26.4	0	3.08	4.6	8	6.34	4.2
10	75	7.6	0	0.11	9.0	0	0.07	10.3	0	5.04	27.1	0	2.64	3.8	10	5.55	3.8
	90	6.2	0	0.12	8.2	1	0.08	7.8	0	5.20	26.4	0	7.83	4.2	10	7.47	4.2
	95	7.8	0	0.14	7.5	0	0.09	8.2	2	5.60	27.7	0	7.59	4.3	8	6.64	4.1
	100	6.6	0	0.19	6.7	0	0.09	6.5	5	7.23	25.5	0	11.29	4.1	5	5.74	3.8
	25	11.8	0	0.27	15.3	0	0.19	14.2	0	8.90	37.5	0	4.36	5.5	10	12.50	5.5
	50	8.7	0	0.50	10.7	0	0.42	12.0	1	8.94	50.8	0	20.46	6.6	9	7.84	6.6
20	75	6.4	2	0.34	7.7	0	0.51	9.5	3	12.55	60.7	0	21.23	5.6	5	14.08	5.2
	90	5.7	2	0.72	6.5	0	0.60	9.9	0	13.07	61.2	0	21.69	5.0	8	8.10	4.9
	95	5.5	1	0.92	6.5	0	0.95	7.8	3	8.32	61.9	0	21.91	4.7	6	9.25	4.6
	100	5.5	1	0.89	6.2	0	0.71	8.5	1	12.89	64.2	0	20.92	4.6	8	9.08	4.5
	25	10.7	1	1.02	13.4	0	0.71	19.0	0	13.57	46.6	0	15.80	7.2	9	20.46	7.1
	50	8.3	1	2.13	9.9	0	1.31	12.0	1	15.16	66.7	0	35.97	7.7	8	19.65	7.3
30	75	6.1	1	2.10	6.6	0	1.64	7.6	2	11.71	75.6	0	36.52	5.4	7	13.35	5.4
	90	4.8	1	3.04	5.1	0	1.85	6.2	2	16.15	78.0	0	36.35	4.4	7	14.46	4.1
	95	4.9	2	3.50	5.1	1	1.90	7.0	1	18.70	78.8	0	36.85	4.6	7	10.32	4.6
	100	4.5	3	3.98	5.1	1	2.05	6.8	1	19.30	78.0	0	36.16	4.3	5	15.68	4.3
	25	11.7	1	2.01	13.8	0	1.68	16.5	0	19.79	63.5	0	53.62	9.1	9	39.40	9.1
	50	7.5	1	3.45	8.5	0	3.04	11.4	0	16.14	78.4	0	57.11	6.4	9	22.64	6.4
40	75	5.4	0	4.54	5.7	0	3.67	7.5	0	25.99	84.5	0	57.57	4.9	10	16.53	4.9
	90	4.4	3	6.20	4.6	0	4.33	6.3	1	29.75	84.1	0	56.80	4.4	6	18.00	4.1
	95	4.0	0	7.43	4.1	0	4.43	5.6	1	25.44	85.7	0	57.06	3.8	9	20.06	3.8
	100	3.9	0	12.21	4.0	0	4.71	5.3	0	16.43	86.0	0	57.23	3.3	10	27.46	3.3
	25	11.2	0	5.21	13.2	0	3.61	15.8	1	45.53	70.8	0	83.06	9.5	9	40.12	9.2
	50	6.7	0	6.74	7.2	1	5.53	10.2	0	20.72	84.5	0	81.84	5.7	9	13.83	5.7
50	75	4.6	3	10.11	4.8	1	7.17	8.1	0	45.99	86.9	0	81.92	4.6	7	22.52	4.4
	90	3.9	1	14.92	3.8	0	8.32	5.8	0	32.28	89.2	0	83.30	3.2	9	39.93	3.2
	95	3.8	2	20.46	3.8	0	8.34	5.6	0	39.59	87.2	0	82.92	3.1	9	37.80	3.1
	100	3.6	2	25.23	3.6	2	8.54	5.2	0	50.03	80.5	1	74.66	3.4	5	32.82	3.4

Table **3**, PC Pentium 100Mhtz. seconds; $\ell = \lfloor 0.75n \rfloor$, average over ten problems.

		*mod*_CMT			*mod*_BL			MS			LS			$\mathcal{X}$-TS			LB
n	d	Δ%	bst	Tbst	Δ%	bst	Tbst	Δ%	bst	Tbst	Δ%	bst	Tbst	Δ%	bst	Tbst	Δ%
	25	8.4	3	0.02	12.1	2	0.00	23.1	0	7.21	5.5	4	3.44	1.8	9	3.07	1.7
	50	10.7	0	0.07	17.1	0	0.05	14.5	0	8.06	18.3	0	6.24	4.1	10	5.29	4.1
10	75	9.9	1	0.15	14.1	0	0.07	15.4	0	5.33	28.5	0	2.66	5.9	9	4.45	5.8
	90	9.7	2	0.19	11.8	0	0.08	16.3	1	4.44	31.1	0	3.44	7.8	7	4.84	7.5
	95	9.9	0	0.20	13.1	0	0.10	13.2	1	7.10	32.8	0	3.28	6.9	9	5.45	6.7
	100	10.3	0	0.21	15.8	0	0.12	15.7	0	5.65	32.5	0	5.33	8.0	10	8.18	8.0
	25	7.4	0	0.31	15.6	0	0.26	26.2	0	7.49	23.0	0	6.53	2.0	10	3.14	2.0
	50	9.5	0	0.65	19.5	0	0.53	21.5	0	12.21	41.8	0	10.01	5.6	10	6.14	5.6
20	75	10.9	1	0.78	17.8	0	0.80	19.5	0	8.91	53.2	0	20.31	8.6	9	3.15	8.6
	90	11.3	2	0.90	18.6	0	1.09	20.7	0	9.71	57.1	0	20.88	9.0	9	7.78	9.0
	95	10.4	2	1.01	17.3	0	1.07	19.5	0	9.34	60.0	0	21.20	8.8	8	3.09	8.6
	100	10.2	1	1.05	15.3	0	1.15	19.5	0	14.32	59.1	0	21.62	8.1	9	1.26	8.1
	25	8.2	0	2.04	16.8	0	0.98	26.0	0	18.19	32.5	0	11.93	2.3	10	7.08	2.3
	50	7.2	0	2.52	14.2	0	2.14	21.8	0	17.20	49.9	0	30.07	3.8	10	4.84	3.8
30	75	11.8	1	2.98	17.9	0	3.66	18.4	0	13.81	71.5	0	35.73	9.6	9	5.10	9.6
	90	9.9	0	3.43	14.3	0	3.65	17.7	0	20.72	78.2	0	35.43	8.1	10	1.35	8.1
	95	9.8	1	3.67	14.6	0	4.04	16.5	0	15.03	78.0	0	36.09	8.1	9	2.48	8.0
	100	9.4	0	3.90	13.5	0	3.98	15.6	0	19.63	78.7	0	35.76	8.0	10	2.75	8.0
	25	8.9	0	2.78	21.0	0	2.96	31.6	0	20.49	45.1	0	27.22	1.4	10	6.73	1.4
	50	9.3	1	4.42	18.6	0	8.03	19.5	0	28.90	69.0	0	56.82	6.3	9	8.81	6.3
40	75	11.0	0	6.25	16.7	0	9.51	18.1	0	27.59	82.3	0	56.12	7.8	10	6.53	7.8
	90	10.3	0	7.51	15.8	0	10.83	16.7	0	27.84	85.8	0	56.29	8.5	10	3.32	8.5
	95	9.4	0	7.92	14.5	0	11.28	17.4	0	28.32	85.6	0	56.73	7.5	10	2.73	7.5
	100	10.2	0	9.12	14.1	0	12.41	15.7	0	35.19	87.6	0	56.92	8.2	10	3.59	8.2
	25	7.4	0	8.02	20.4	0	7.27	27.8	0	54.31	45.6	0	56.48	1.3	10	11.80	1.3
	50	8.4	0	9.63	17.4	0	14.45	17.0	0	42.11	73.2	0	82.11	5.9	10	1.21	5.9
50	75	10.6	0	11.21	16.6	0	19.87	16.5	0	35.77	86.0	0	83.45	8.4	10	1.55	8.4
	90	9.4	0	13.34	13.4	0	22.38	14.8	0	42.69	90.0	0	83.81	7.8	10	1.81	7.8
	95	8.7	0	15.36	13.0	0	23.64	13.9	0	46.12	89.5	0	83.14	7.4	10	5.08	7.4
	100	8.5	1	23.31	12.1	0	25.42	14.4	0	53.95	90.2	0	82.37	7.4	9	2.39	7.3

Table 4, PC Pentium 100Mhtz. seconds; $\ell = \lfloor 0.9n \rfloor$, average over ten problems.

		*mod*_CMT			*mod*_BL			MS			LS			$\mathcal{X}$-TS			LB
n	d	Δ%	bst	Tbst	Δ%	bst	Tbst	Δ%	bst	Tbst	Δ%	bst	Tbst	Δ%	bst	Tbst	Δ%
	25	14.2	0	0.05	14.0	0	0.01	24.9	0	6.18	4.5	3	4.33	1.0	9	3.35	0.9
	50	11.0	1	0.12	15.6	0	0.02	25.1	0	5.50	13.6	0	5.29	1.6	9	6.51	1.4
10	75	7.2	1	0.19	16.4	0	0.08	17.2	0	10.06	19.2	0	5.21	2.0	9	6.68	2.0
	90	6.9	5	0.22	16.9	0	0.11	18.2	0	6.86	30.3	0	4.08	5.6	6	4.45	4.9
	95	7.9	0	0.21	15.5	0	0.10	18.3	0	6.06	25.0	0	2.80	3.7	10	4.14	3.7
	100	9.5	1	0.24	18.2	0	0.12	19.5	0	6.27	29.9	0	2.74	6.0	9	4.62	5.9
	25	11.3	0	0.44	17.6	0	0.15	35.4	0	12.34	20.5	0	10.98	1.6	10	2.92	1.6
	50	11.7	0	0.71	25.1	0	0.60	37.2	0	11.11	38.1	0	11.60	1.2	10	3.26	1.2
20	75	7.4	0	0.82	20.9	0	0.88	25.2	0	14.03	41.2	0	15.20	2.7	10	0.91	2.7
	90	9.0	0	1.03	20.3	0	1.26	26.3	0	8.41	48.5	0	20.54	4.0	10	5.72	4.0
	95	8.9	0	1.12	19.8	0	1.28	25.9	0	10.45	50.2	0	19.74	4.7	10	3.72	4.7
	100	9.2	0	1.09	19.4	0	1.27	24.1	0	10.98	49.8	0	20.40	5.1	10	1.06	5.1
	25	14.3	0	3.04	24.3	0	0.80	42.9	0	10.59	29.8	0	14.39	1.4	10	5.06	1.4
	50	7.3	0	12.22	20.4	0	3.05	34.7	0	13.94	42.5	0	24.84	0.7	10	0.94	0.7
30	75	7.8	0	3.11	20.6	0	4.49	25.2	0	24.08	56.1	0	34.40	2.7	10	1.91	2.7
	90	7.7	0	3.69	19.9	0	5.16	24.8	0	16.31	64.3	0	34.63	3.1	10	1.17	3.1
	95	8.3	0	3.84	20.2	0	5.76	25.6	0	13.42	66.6	0	33.61	4.3	10	1.25	4.3
	100	9.7	0	4.01	20.2	0	5.68	24.7	0	19.15	70.4	0	34.95	5.0	10	4.65	5.0
	25	15.4	0	3.02	31.4	0	2.79	53.0	0	23.46	44.1	0	24.16	0.2	10	0.87	0.2
	50	9.2	0	7.34	25.6	0	9.52	37.5	0	27.29	52.6	0	52.00	0.1	10	1.18	0.1
40	75	7.2	0	7.05	20.7	0	13.21	24.5	0	26.86	65.3	0	53.94	1.8	10	3.34	1.8
	90	8.7	0	8.62	21.0	0	15.21	24.1	0	26.30	72.3	0	51.33	4.1	10	1.33	4.1
	95	8.9	0	8.94	19.5	0	16.03	26.4	0	27.54	76.4	0	55.57	3.7	10	2.07	3.7
	100	8.9	0	45.76	19.7	0	17.70	23.5	0	38.91	74.9	0	55.57	4.2	10	3.40	4.2
	25	15.5	0	9.32	30.6	0	7.05	51.9	0	38.78	45.8	0	48.45	0.1	10	0.91	0.1
	50	6.9	0	10.20	24.3	0	23.39	30.9	0	31.75	56.8	0	60.14	1.1	10	1.86	1.1
50	75	8.1	0	14.38	21.7	0	31.98	23.5	0	35.04	67.5	0	80.97	2.6	10	2.19	2.6
	90	8.9	0	16.21	19.9	0	33.89	23.1	0	41.97	69.3	1	74.99	4.0	9	1.74	4.0
	95	8.8	0	17.34	21.1	0	39.33	23.1	0	43.79	80.0	0	77.58	4.3	10	1.81	4.3
	100	9.5	0	56.12	20.1	0	40.73	23.2	0	43.24	80.5	0	78.39	5.4	10	1.93	5.4

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