A survey on TDMA satellite systems and slot allocation

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1 Introduction

We present in this survey several aspects of TDMA satellite systems. We focus in particular on algorithmic approaches for slot allocation (or "burst scheduling") algorithms. We mention however also other issues that are related to TDMA systems: architecture, synchronization, some physical layer considerations, and papers presenting probabilistic performance evaluation techniques.

A few words on terminology. We use the standard term SS/TDMA for Satellite Switch TDMA. We also frequently find in the literature the term of "burst" scheduling. The term "burst" does not refer to a burst in the input traffic but rather to the burst caused by the fact that traffic is not transmitted continuously. The input to the slot assignment problem in TDMA is often a traffic matrix whose ijth element describes the amount of traffic to be shipped from zone i to zone j.

2 Algorithmic approach for slot allocation

2.1 Early papers

The paper [13] considers a satellite with several spot beam antennas. The paper considers the time slot assignment problem that consists in scheduling the network burst traffic requirements. A TDMA frame is divided into a number of switching modes, and 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. The scheduling goal is to maximize the satellite transponder utilization with a minimum number of switching modes. The input to the optimization problem is the traffic matrix. Propositions for improving the assignment of [13] are given in [26], and are validated through simulations.

In [1] the authors consider an SS/TDMA system with M uplink beams, N downlink beams, and $K, 1 \leq K \leq \min(M, N)$ transponders. An optimal time slot assignment algorithm for any M, N, K, and any traffic matrix is presented, where optimality means achieving the minimal possible total duration for the given traffic matrix. The number of switching matrices generated by the algorithm is bounded above by $N^2 - N + 1$ for $K = M = N$ and $MN + K + 1$ otherwise. Extensive simulation results on randomly generated matrices are carried out, showing that the average number of switching matrices generated is substantially lower than the bounds.

In [10] the authors study the traffic scheduling problem in an SS/TDMA system with interfering beams. They present a two step approach, (i) the assignment of orthogonal polarization to reduce the interference, and (ii) the scheduling of traffic, taking into account the "resultant" interference. The authors show that the first step can be solved in polynomial time in most cases, while the second step is proved to be NP-complete, even for very simple interference patterns. The authors suggest several suboptimal algorithms for this second step and, by experimental trials on randomly generated traffic patterns, show that on the average they produce close to optimal solutions.

In [12], the authors investigate the problem of constructing a TDMA frame for a multi-beam satellite system. The objective is to permit the transmission of a given pattern of traffic, while ensuring that the number of times that the on-board switch needs to be re-configured is minimized. The authors find that the underlying optimization problem is computationally intractable, but suggest an efficient heuristic algorithm which is validated through experiments on randomly generated traffic patterns.

A previous related paper by these authors is [11] that studies the problem of time-slot assignment in an SS/TDMA system operating in a packet-switched environment. The goal there is to assign time slots in order to minimize average packet waiting time and in order to maximize transponder utilization. It is shown that an assignment which achieves both objectives exists and the authors develop a branch-and-bound algorithm to find it. In addition, they suggest several heuristics which require much less computational effort and give very close to optimal results. Theoretical bounds on the performance of these heuristics are obtained, and are validated through simulation. The later show that on average, the heuristics are better than their bounds suggest, and are, in fact, close to optimal.

An empirical approach for burst scheduling has been proposed in [19, 18, 27].

Reference [22] studies the time-slot assignment problem for SS/TDMA where only a restricted set of all possible switching modes is to be used. An efficient algorithm for finding an optimal assignment is proposed. Also, methods for selecting restricted sets of switching modes are presented. The paper improves upon the complexity in [13, 14, 27].

The type of problem studied and the results obtained in the previous references is later extended in [2, 3, 5, 20, 21].

2.2 Recent papers

In [20] the problem is to obtain a time slot assignment given a network configuration and user traffic requirements in SS/TDMA networks. The problem is formulated as a bipartite graph matching problem. A so called "max-min" algorithm is used as a heuristic to reduce the number of switching reconfigurations by assigning as large a burst as possible at each step. The bipartite graph approach is compared to an alternative circulation formulations of the TDM switching assignment problem in [21]. Some properties of the circulation formulation is given as well as a polynomial assignment algorithm. It is Bonouccelli [2] who initially formulated the slot assignment as a circulation problem, of finding a feasible circulation in a source-free and sink-free network that satisfies prescribed lower bounds and capacities (on upper bounds) on the flow values in arcs.

In [3], Bonouccelli extends his previous work [2] and considers the problem of two types of traffic are considered: a rapidly changing type composed of packet-switched data and a relatively static type composed of circuit-switched voice traffic. The problem is to construct an efficient TDMA frame that permits the static voice traffic to be transmitted and then on a frame-by-frame basis, to attempt to insert the data packets in the slots unused by the voice traffic. This problem is shown to be NP-complete and heuristics algorithms are proposed and tested.

In [5], the authors present efficient sequential and parallel algorithms for computation of time-slot assignments in SS/TDMA (satellite-switched/time-division multiple-access) systems with variable-bandwidth beams. These algorithms are based on modeling the time-slot assignment (TSA) problem as a network-flow problem. The sequential algorithm, in general, has a better time-complexity than a previous algorithm due to Gopal, et al. [10] and generates fewer switching matrices. If M (N) is the number of uplink (down-link) beams, L is the length of any optimal TSA, and a is the maximum bandwidth of an uplink or down-link beam, the sequential algorithm takes $O((M+N)^3 min(MN\alpha, L))$ time to compute an optimal TSA when the traffic-handling capacity of the satellite is of the same order as the total bandwidth of the links. The parallel algorithm uses L/2 processors and has a time-complexity of $O((M+N)^3 \log L)$ on a PRAM model of parallel computation. The authors generalize this algorithm to $P \leq L/2$ processors and describe an efficient implementation of the algorithm on a hypercube multiprocessor with P processors. A massively-parallel version of the algorithm is shown to run in $O((M+N)^2 \log(M+N) \log L)$ time on $(M+N)L/2$ processors.

Efficient algorithms that generate a detailed operation plan for SS/TDMA systems are proposed in [24]. A burst time plan generation problem is analyzed and two algorithms for burst scheduling are presented. The first method is an algorithm based upon a bin pack problem. The other algorithm schedules new bursts while reassigning already scheduled bursts by a single machine scheduling model. These algorithms are shown to be applicable to practical systems operating with transponder hopping and multi-destination bursts. Simulation results for a number of example problems are presented.

2.3 Other work

We should mention that the time slot allocation in a TDMA system has been studied not only in the satellite context. We mention some references in the more general context.

The slot allocation in a TDMA multiplexed switching systems which can support multicast transmissions is studied in [6]. It is shown that this problem is NP-complete. Two effective heuristic algorithms are proposed, and computer simulations are also performed to evaluate the performance of both algorithms. The results of the simulations indicate that the solutions generated by these heuristic algorithms are very close to the optimal on the average. In addition, this problem is also examined under a more restrictive condition that the destination sets of any two multicast packets are either identical or disjoint, a situation often encountered in many practical applications. It is proved that this special problem is still NP-complete. Two fast heuristic algorithms are given, which can find solutions not greater than twice the optimal solution. Computer simulations for evaluating these two heuristic algorithms are also performed. Experimental results demonstrate that the solutions of the two algorithms are almost equal to the optimal.

The paper [9] presents a parallel algorithm for time-slot assignment problems in TDM hierarchical switching systems, based on the neural network model The TDM systems are operated in repetitive frames composed of several time-slots. A time-slot represents a switching configuration where one packet is transmitted through an I/O line. The goal of our algorithm is to find conflict-free time-slot assignments for given switching demands. The algorithm runs on a maximum of $n^2 \times m$ processors for m-time-slot problems in $n \times n$ TDM systems. In small problems up to a 24 24 TDM system, the algorithm can find the optimum solution in a nearly constant time, when it is performed on $n^2 \times m$ processors.

Two efficient time slot assignment algorithms, called the two-phase algorithm for the non-hierarchical and the three-phase algorithm for the hierarchical time-division multiplex (TDM) switching systems, are described in [29]. The idea behind these two algorithms is to schedule the traffic on the critical lines/trunks of a traffic matrix first. The time complexities of these two algorithms are found to be $O(LN^2)$ and $O(LM^2)$, where L is the frame length, N is the switch size, and M is the number of input/output users connected to a hierarchical TDM switch. Unlike conventional algorithms, they are fast, iterative and simple for hardware implementation. Since no backtracking is used, pipelined packet transmission and packet scheduling can be performed for reducing the scheduling complexity of a transmission matrix to $O(N^2)$ and $O(M^2)$, respectively. Simulations reveal that the two proposed algorithms give close-to-optimal performance under various traffic conditions.

Finally, another related paper that should be mentioned is [23].

3 Papers presenting architecture, equipments and physical layer considerations

In [16], an overview of architecture and equipment for TDMA satellite is given: burst modems, baseband switches, and SCPC (Single Channel per Carrier) multi-carrier demodulators along with device technology development trends, in terms of minimizing on-board weight and power consumption. The results show that at the time the paper is written (1990), on-board TDMA equipment with a clock rate of lower than 100 MHz can be reasonably realized by parallel-processed CMOS/BULK LSIC's, while for TDMA equipment with clock rates of higher than 100 MHz, bipolar devices are more appropriate. The boundary clock rate is not so rigid, and it is predicted that toward the year 2000, the boundary will move up to about 200 MHz. Moreover, around the year 2000, GaAs devices will be more widely used for on-board high-bit rate TDMA.

A combination of FDMA and TDMA for satellite access is used in the ACTS (advanced communications technology satellite) experimental communications satellite of NASA's Lewis Research Center. The system architecture is described in [25] Low burst rate (LBR) traffic stations access the ACTS multi-beam communications package (MCP) through two hopping beams that can be directed at certain cities and areas in the continental United States. An on-board baseband processor (BBP) demodulates uplink traffic received via two up-link (30

GHz) hopping beams, switches the traffic between uplink and downlink beams at baseband, and then remodulates the traffic for retransmission at 20 GHz via two downlink hopping beams. This study concentrates on the demand assigned operation of the ACTS LBR system where the on-board switch is remote from both the traffic stations and the centralized master control station (MCS). Network control uses inbound and outbound orderwire channels and a BBP control channel thereby allowing the MCS to coordinate assignment of individual 64-kb/s channels in the spacecraft. Models are developed to simulate the dynamics of the demand assignment process in order to verify call blocking behavior, to predict control channel loads, and to evaluate alternative algorithms for burst time plan rearrangement that becomes necessary to minimize blocking under conditions of high-traffic intensity.

In [17], the authors propose a TDMA satellite network where channels are assigned on demand basis. The system is designed for both basic as well as primary ISDN rates: it offers subscribers a range of throughputs between 64 kbps to 1536 kbps. The paper considers multi-carrier transmission (by carrier hoping) per transponder (such as used in INTELSAT TDMA systems) which generates adjacent channel interference problems. The paper discusses in details the lower network levels (physical and link levels): the chosen modulation, the FEC used, the structure of the TDMA channel and frame format.

In [8], the authors consider the traffic handling capability of a new switching architecture which generalizes upon the structure of a traditional time multiplex switching system. For the traditional approach, low bandwidth end users are formed into groups, each of which shares a single high bandwidth time-division multiplexed (TDM) line into the central time multiplex switch. Each user synchronously generates packets of data in preassigned time slots at a rate consistent with its offered traffic, and the feeder for the TDM line serving a group of users merely time multiplexes the arriving packets prior to routing by the central switch; analogously, each output port of the switch feeds a demultiplexer which routes the packets to the appropriate user within its group. The generalized approach permits each user group to share some multitude of TDM lines interconnecting that group with the central switch, and the group multiplexers and demultiplexers are replaced by switches which route packets from users to TDM lines (and vice versa). For this structure, the authors derive a set of necessary and sufficient conditions on the offered traffic such that a valid, nonconflicting TDM assignment of packets-to-time slots exists. These conditions reveal that the constraints imposed by the three-tiered switching hierarchy do not limit the useable capacity of the switch. Consequently, with no loss of traffic bearing efficiency, it is possible to reduce the number of multiplexers used to serve the end-user population, achieve greater trunking efficiency since small user groups served by one TDM line are replaced by larger groups serving multiple lines, and modularly grow the system by adding TDM lines to each group commensurate with the traffic offered by that group. As a byproduct, it is shown that such a system designed to switch low-speed circuits of some particular data rate can, with no hardware change, switch circuits at lower rates (subrate switching). These conclusions have important ramifications for the design of terrestrial and satellite-based switching systems.

The paper [4] deals with the scheduling control of single burst both in a single beam as well as in a multi-beam TDMA satellite systems. More precisely, it focuses on a specific concept of control used by a station to acquire and synchronize its burst transmission to the assigned time slot(s).

We should finally mention a survey paper [30] that surveys recent KA-band satellite systems.

4 Probabilistic performance analysis

Reference [15] analyzes the performance of demand assignment TDMA multi-carrier TDMA satellite networks. When an earth station wants to connect to another earth station through a satellite, a switched-circuit has to be opened. The freeze-out (probability that a circuit cannot be established due to capacity constraints) probability is computed. Expressions are derived for the necessary satellite capacity for specified traffic.

In [28], an analysis is presented of the traffic performance of a variable-channel-per-burst (VCPB) approach for SS-TDMA that dynamically reconfigures traffic bursts. An SS-TDMA system with an on-board baseband switch is used as the VCPB application system. Bursts are assigned to each earth station one-by-one. Idle channels of other bursts are transferred to a burst having an insufficient number of idle channels by reconfiguration on a call-by-call basis. The VCPB is suited to SS-TDMA systems with relatively few earth stations. VCPB traffic performance depends on the reconfiguration strategy. The effects on traffic performance caused by reallotting idle channels to all bursts in every reconfiguration are described. An approximate formula for the reconfiguration probability from the loss probability of fixed-channel-per-burst TDMA weighted by the binomial distribution for the number of channels in each burst is derived.

In [7], a performance analysis to compute the packet loss, call blocking, and packet delays of a typical user in an integrated voice-data-video satellite inter-networking environment is discussed. The uplink technique used is a hybrid packet/circuit switched approach of the demand assignment type, while the downlink is a time-division-multiplexing (TDM) technique. Onboard the satellite, a baseband nonblocking switch is used to route the packets from input to output ports. Various amounts of input and output buffering as well as priority rules and blocking resolution algorithms are used. Using a Markovian analysis, the authors conduct a performance analysis for the problems at hand and identify the best ranges for the different parameters involved.

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