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LA THÈSE A ÉTÉ  
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AN OPTIMAL TDMA SLOT ASSIGNMENT IN MULTIBEAM PACKET  
SATELLITE SYSTEMS

by

FOUAD G. KARAM

A thesis  
presented to the university of Ottawa  
in fulfillment of the  
thesis requirement for the degree of  
Masters of Applied Science  
in  
The Department of Electrical Engineering

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## ABSTRACT

This thesis is concerned with the optimization of a multibeam packet satellite system. Such a system includes  $M$  transponders that can be switched to cover  $N$  service zones. The traffic from each user in a group is concentrated in a central switching office which handles the uplink transmissions. For the system, the average packet delay and the total throughput are defined and computed mathematically, and by introducing an optimization algorithm, the system performance is enhanced. Several computations are needed for this matter. A straight-forward procedure has to be followed for the application of these results in a realistic system.

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## Chapter I

### INTRODUCTION

When communications satellites were first launched, they were used exactly in the same way terrestrial cables were used for point-to-point communication. For example, a transatlantic satellite connected carrier offices on either side of the ocean. The carrier could route a particular call over the satellite link or over the cable. The satellite represented a big cable-in-the-sky.

This type of usage had some advantage at that time due to the fact that satellite earth stations were expensive, making it unlikely many people would decide to buy one of their own.

In the last two decades, the situation has changed completely. The price of ground stations has dropped, and the cost of computer interfaces went a way down; also, the growth of telecommunications for transmitting data has been enormous, bringing with it a demand for communication channels with much higher bandwidth and a much lower error rate.

These reasons suggested further development of the mode of operation of the satellite. The key ingredient is that the decision of how to allocate the satellite channel must be made using the channel itself.

The main question in a system having a single communication channel that must be shared efficiently among a large number of widely dispersed, and uncoordinated users is, how to share this channel? If everyone just begins transmitting whenever he wants, regardless to what the others are doing, conflicts may result and there will be no communication at all. From this point, rises the issue of channel assignment.

In recent years, many wideband satellite communication systems have been used to link together a large number of earth stations. The Satellite-Switched Time Division Multiple Access Method (SS/TDMA) is one of the most effective techniques designed for allocating the communication bandwidth provided by a satellite link to carry the bursty traffic between the earth stations [2].

The (SS/TDMA) technique utilizes the merits of high gain spot beam antennas, along with the efficient TDMA method for providing complete connectivity of coverage areas. A satellite embodies several spot beam antennas and a switch, which periodically switches the connections of uplink and downlink beams to facilitate interconnectivity of beam zones. A spot beam satellite offers

a large frequency reuse without crowding the frequency spectrum [4].

In Chapter I, some random access techniques used in satellite communications are presented. First, the packet switching technique is described, and its mode of operation is discussed. Then, the well-known ALOHA protocol is introduced, and the system measures are evaluated in terms of network throughput and packet delay.

Chapter III is a complete representation of the satellite system under study. All the assumptions are stated clearly; the throughput and average packet delay are evaluated with some numerical examples.

Chapter IV takes care of the system optimization. This is the main contribution of this thesis. The maximum throughput and the minimum packet delay are computed in terms of slot assignments and channel allocation.

---

## Chapter II

## RANDOM ACCESS TECHNIQUES.

2.1 PACKET SWITCHING

The origins of packet switching are more strongly based in voice communications than in data communications, though packet switching is now more widely applied to data on computer-based communications.

The idea started with the notion of breaking a voice conversation between two parties into short, separate pieces (packets). At each switch, the pieces of a call would be mixed with pieces of other calls and sent, piece by piece, over several different routes to the destination (fig. 1).

2.1.1 Basic Concepts

The concept of packet switching, using discrete switching elements in a distributed network, is based upon the ability of modern high-speed digital computers to act on transmitted information, so as to divide the calls or messages into pieces called packets. Packets move around the network, from switching center to switching center, on a hold-and-forward basis; that is,

each switch holds a copy of each packet in temporary storage until the switch is sure that it has been received properly by the next switch or by the destination user. This form of operation permits the network to achieve low overhead for short messages and eliminates the set-up time for calls that is required in conventional circuit switched telephone networks. Because all communications are broken down into similar component pieces, long messages and short messages can move through the network with a minimum of interference with each other. By moving the packet through the network in real time, the switches can adapt their operation quickly in response to changing traffic patterns or a failure of part of the network.

Many different implementations of packet switching have been developed, which, though they all provide standard user interfaces, are largely incompatible on a switch-to-switch level. As a result, the interoperation of different networks has to take place at a fairly high-level of protocol through interface gateways. The gateway is a process that transforms the internal message structure of the originating network into an input format accessible to the network that contains the destination subscriber.

### 2.1.2 Network Operation

Figure 2 illustrates a portion of an arbitrary packet switched network. For short messages that can fit into a single packet,

the operation of any network is quite simple. The complete message contained within a single packet, simply moves as a discrete entity from one user to the other, following a path through the network selected by the switching elements. In fact, the concept of message handling, where the entire message is required to fit within a single packet, is defined by a packet switched mode of operation known as datagram.

It is only when messages extend beyond the limit of a single packet that more complex data management protocols come into play. The ability of packet networks to handle multiple-packet messages requires the application of numerous checks in the operational protocols to protect against various arising problems. What is known as virtual circuit operation of a packet switched network, provides a number of steps directly analogous to normal telephone operation. Virtual circuits have to be established through the network on the basis of a new call request. Once the virtual circuit is established, packets flow on a continuous basis from user to a user, almost as if a fixed connection existed between end-points.

## 2.2 THE ALOHA TECHNIQUE

### 2.2.1 The ALOHA Protocol

The ALOHA protocol [2] provides the most fundamental approach to a fully distributed network. The mode of operation of this protocol is suggested by its name (Good Bye). System operation is based upon the users initiating transmission into the common system whenever they have a new message to transmit.

### 2.2.2 The Operational Environment for ALOHA Systems

Figure 3 shows a group of users each broadcasting to a central processor. The broadcast takes place over a commonly available satellite channel using a synchronous satellite 22,300 miles above the equator. Because of the long distance the transmission must travel, it takes about one-fourth of a second for a signal to reach the satellite and be returned to earth. Since all users are presumed to have identical earth stations, each user can receive the communications from all other users and can also hear his own transmissions. Though the satellite retransmits exactly what it receives, it is more than just a mirror-in-the-sky. The satellite receives signals transmitted on the uplink frequency, amplifies them, and retransmits them on a different downlink frequency. All

users in the system transmit on the same uplink frequency and listen to the same downlink frequency. Although the ALOHA technique is not dependent on any particular data rate, it will be easiest to explain the operating principles in terms of a particular set of data rates. Let us assume, that the channel is operating at a rate of 50 Kbits/sec, and that each user sends his data in packets of 1000 bits each. A packet will have a duration of 20 msec, which is relatively short compared to the 250 sec roundtrip delay.

### 2.2.3 Transmissions and Collisions

Figure 4 illustrates the typical occurrences in the ALOHA channel. The figure shows each user's uplink transmission separately, and at the bottom, the combined downlink transmission heard from the satellite. We choose a packet length of 20 msec. We see that packets sent by users 2 and 4 will overlap and then be destroyed. There will be a collision. It is assumed that if any part of a packet is damaged, the entire packet has to be retransmitted. It is also assumed that the collision of two packets damages both of them equally, which is a worst case assumption. After the time of one roundtrip propagation has elapsed, user 2 and user 4, both listening to the common downlink, hear the collision of their packets, and each transmits a repetition packet to replace the damaged packets. However, an immediate retransmitted packet has the same chance to collide again. In order to minimize the probability

of a second collision, both users select a random delay time before attempting the retransmission.

#### 2.2.4 Performance of the ALOHA Protocol

Now that the mode of operation of the ALOHA protocol has been explained, we wish to determine the throughput and delay of the channel to user traffic.

The Poisson process mathematically describes the probability associated with the actions of a large number of statistically unrelated users, on the basis of their average message rates. The probability that a large group of uncorrelated users will generate exactly  $N$  new packets during a time interval  $t$  seconds large is:

$$P(N) = \frac{(\lambda t)^N \cdot e^{-\lambda t}}{N!}$$

where  $\lambda$  is the average packet arrival rate.

The probability that user 1's packet is successful, is the same as the probability that exactly zero other packets are transmitted during the time interval  $2\tau$  seconds.

$$P_S = e^{-2\lambda\tau}$$

where  $\lambda'$  is the sum of originating and retransmitted packets and  $\zeta$  is the packet duration.

The probability of success is the ratio of successful outcomes over the total number of trials.

$$P_S = \lambda / \lambda'$$

By multiplying both sides by the packet length  $\zeta$ , we obtain:

$$S = g e^{-2g}$$

$S$  is the channel throughput,

$g$  is the normalized channel traffic.

An approximate plot of the above relation is shown in figure 6.

#### 2.2.5 Delay in the ALOHA Channel

Figure 5 illustrates the elements of the delay associated with a single packet message through the ALOHA channel. The packet is initially transmitted, which takes  $\zeta$  seconds. After  $N$  seconds of round-trip propagation delay, the packet is received, possibly with

interference. If a collision occurred, however, the protocol requires that the sender waits for a random period, between zero and  $K$  packet times, before retransmitting, in order to minimize the probability of a second collision. On the average users have to wait

$$(K + 1) \frac{\zeta}{2}$$

seconds before attempting retransmission.

The total average delay is therefore [2]:

$$D = \zeta + N\zeta + (e^{2g} - 1) \left[ \zeta + N\zeta + \frac{(K + 1)}{2} \zeta \right]$$

A plot of  $D$  versus  $S$  is shown in figure 7.

### 2.3 SLOTTED ALOHA PROTOCOL

The slotted ALOHA channel protocol decreases the probability of interference between packets, by requiring that users transmit only at the beginning of discrete time intervals. This kind of channel protocol means that two users can interfere with each other only if they transmit at exactly the same time. If only one user transmits at the beginning of a packet interval, his packet is guaranteed no

interference since no other user is permitted to transmit until the beginning of the next interval. This technique is capable of effectively doubling the channel capacity at only a small increase in the average delay.

### 2.3.1 Analysis of the Slotted ALOHA Channel [2]

We assume that every packet is filled to maximum length and thus does not waste any capacity between the end of one packet and the beginning of the next allowable time slot.

We begin with the following definition:

$S_1$  = the probability that user 1 successfully transmits a packet.

$g_1$  = the probability that user 1 transmits any packet.

For user 1 to transmit a successful packet, since this is a slotted case, he must transmit his packet while no other user transmits one. Mathematically, this can be stated by:

$$S_1 = \frac{g_1 (1-g_1) (1-g_2) \dots (1-g_N)}{(1-g_1)}$$

All terms are included in this equation for all  $N$  possible users of the channel. The expression is divided by

$$(1-g_1)$$

since user  $i$  is transmitting. This means that the probability of user  $i$  transmitting a successful packet is the probability that all other users are not sending any packet.

$$S_i = g_i \prod_{\substack{j=1 \\ j \neq i}}^N (1-g_j)$$

An assumption has to be made at this point. All users are statistically equal, they share the capacity equally. Therefore:

$$S_i = S / N \quad g_i = G / N$$

where  $S$  and  $G$  are the channel throughput and channel traffic respectively

$$S = G (1-G/N)^{N-1}$$

For large number of users,  $(1 - X/N)^{N-1}$

approaches  $\text{EXP}(-X)$ ; this results into:

$$S = G e^{-G}$$

The relationship between channel throughput and channel traffic is shown in figure 8.

The delay associated with the slotted ALOHA channel can be derived in the same way the unslotted delay was found. The only difference is that, on the average, each time a user is ready to make a transmission, he has to wait one-half of a packet time until the beginning of the next slot interval before he can actually transmit.

The total average packet ~~delay is:~~

$$D = \zeta + \frac{\zeta}{2} + N \zeta + (e^G - 1) \left[ \zeta + \frac{\zeta}{2} + N \zeta + \frac{(K+1)\zeta}{2} \right]$$

Figure 1: A packet switched network for voice communication [2].

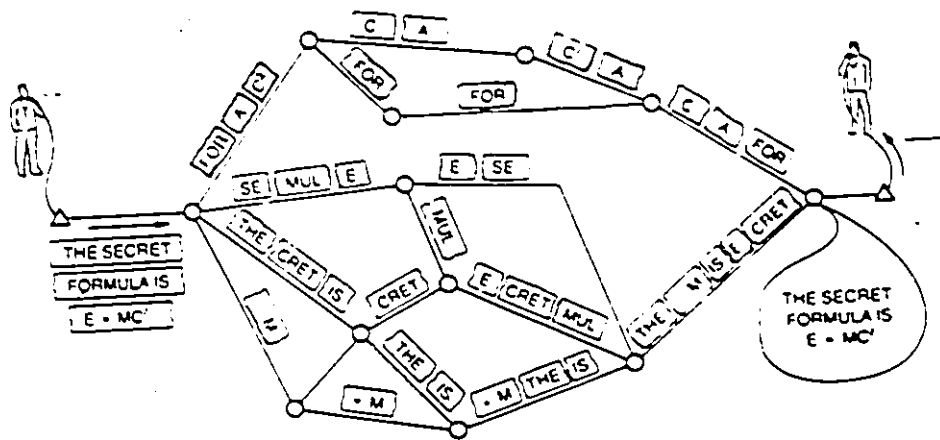


Figure 2: Basic operation of a packet switched network [2].

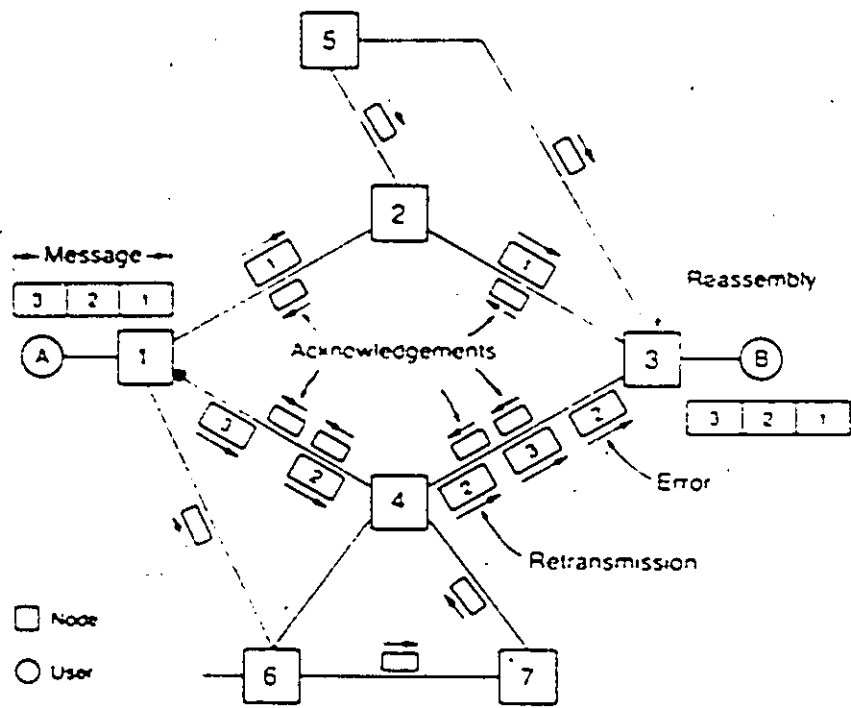


Figure 3: A distributed network [2]

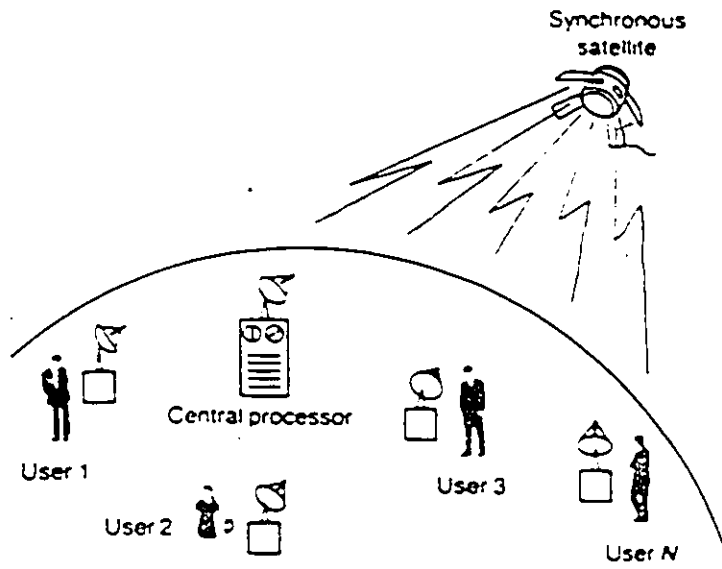


Figure 4: Typical occurrences in an ALOHA channel [2].

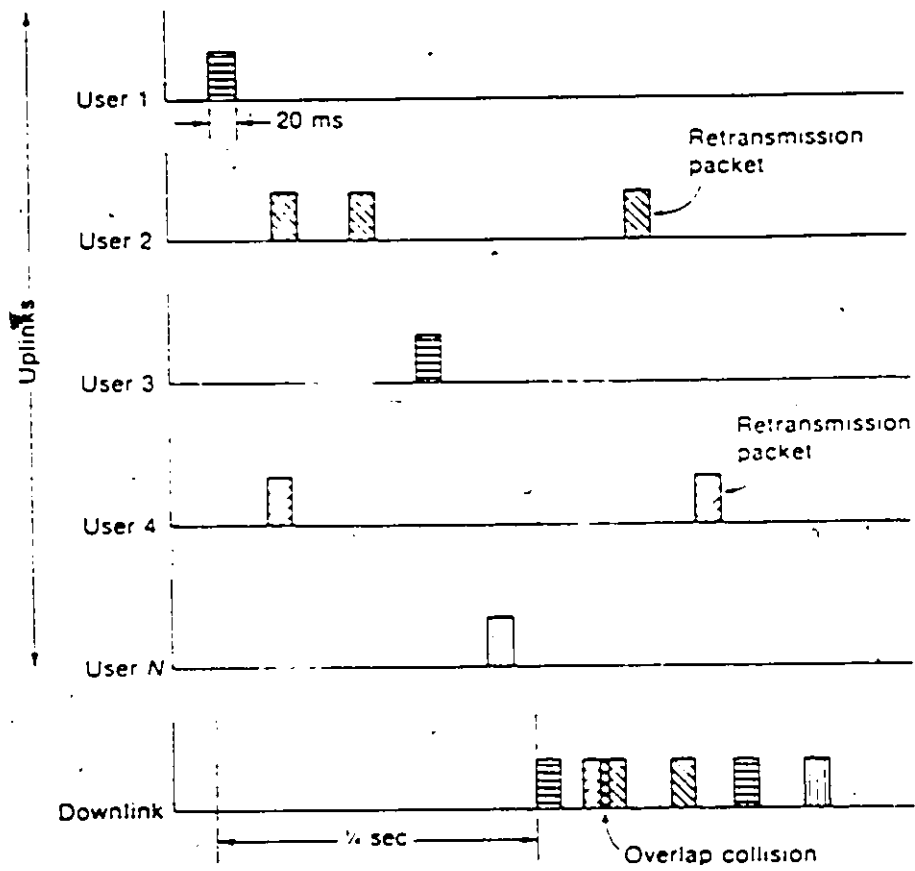


Figure 5: Delay in ALOHA channel [2].

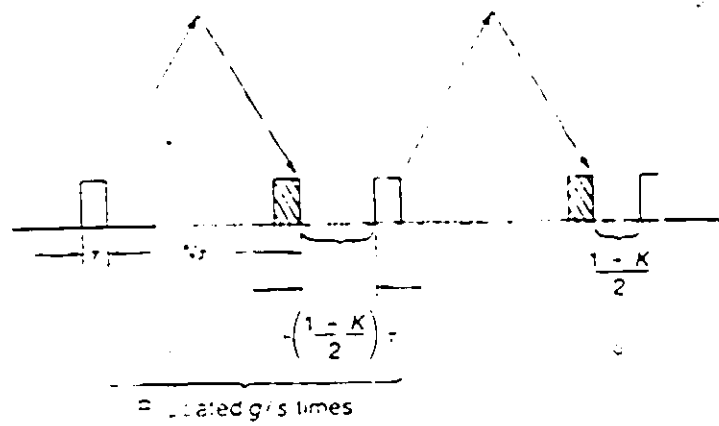


Figure 6: Throughput vs channel traffic for pure ALOHA [2].

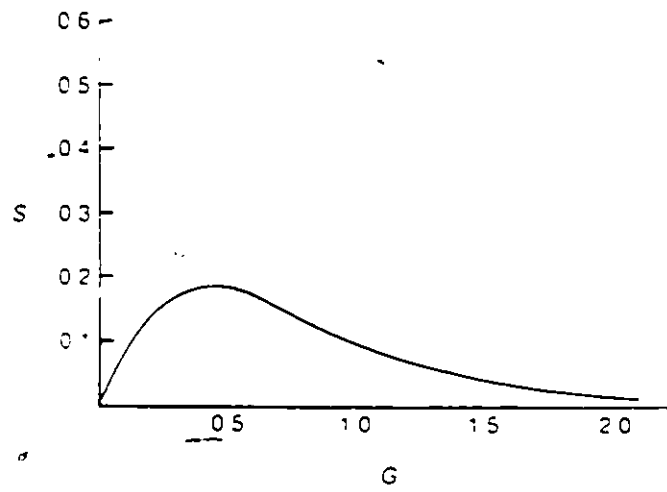


Figure 7: Plot of channel delay vs channel throughput [2].

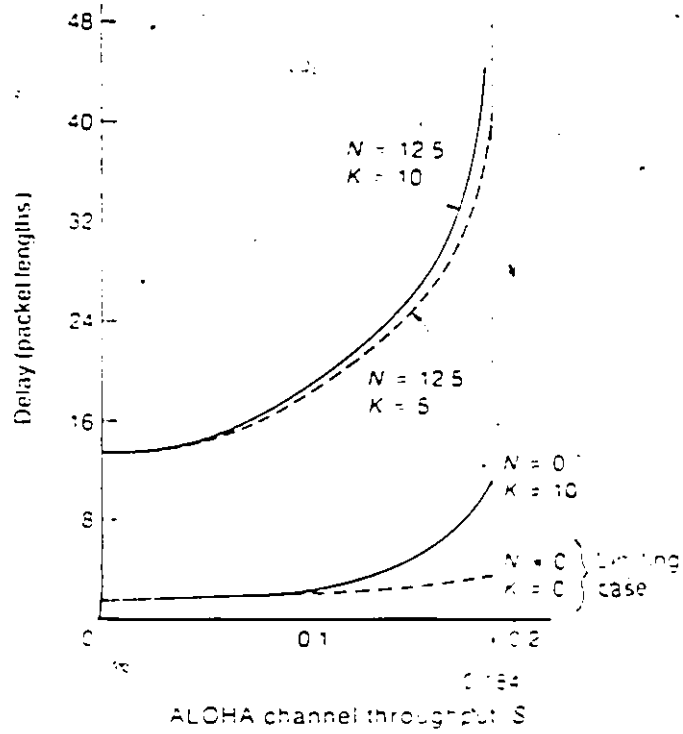
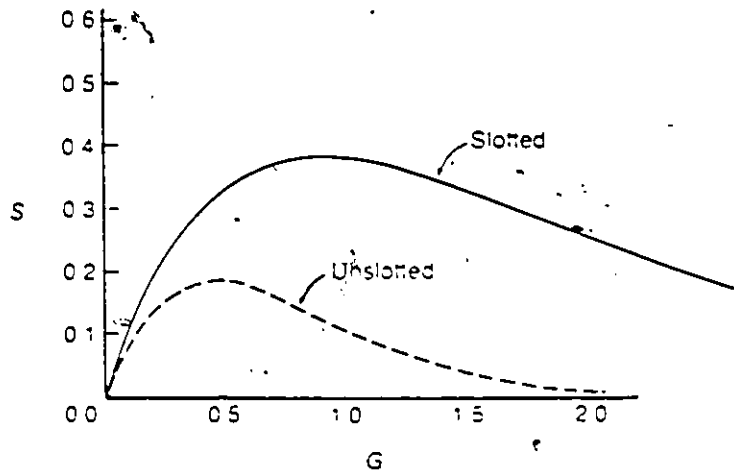


Figure 8: Channel throughput vs channel traffic for slotted ALOHA [2]



## Chapter III

CONFIGURATION AND ANALYSIS OF A MULTIBEAM  
SATELLITE SYSTEM3.1 INTRODUCTION

The (SS/TDMA) slot assignment problem in a multibeam satellite has been studied extensively [3] to [7]. However, one common assumption made in these papers is that the traffic within one zone must be concentrated at the earth station in that zone and then routed through the satellite repeater. In this chapter, we will study the performance of a multibeam packet satellite system using a given protocol. These results come from [1].

3.2 THE MULTIBEAM SATELLITE SYSTEM

Figure 9 depicts the configuration of the system to be considered. This system can be divided into three major parts, the switch and transponders, the antenna network, and the spot beams that cover the entire area.

The satellite is employing  $M$  identical wideband transponders, each one used at its full capacity. Given the number of spot-beam zones  $N$ , the system traffic can be represented by an  $N \times N$  matrix. On board the satellite, there exists a switching matrix that directs

the traffic from one zone to another. The number of spot beam zones is determined by the size of the antennas used in the antenna network. The reason for dividing the entire coverage area into spatially disjoint beam zones is to accomplish frequency reuse in the multibeam system.

In the space segment, we consider a system whose antennas are arranged to form  $N$  non-overlapping spot-beams, each serving a separate zone. Each beam comprises one uplink and one downlink at different carrier frequencies, with a connections mode between up and downlinks through a switch matrix in the satellite. Each connection represents a path through one of  $M$  frequency translating transponders, and we allow for the case where they may be fewer transponders than zones. Such a system may be thought of as having many scanning beams, one associated with each transponder. We assume that there are a number of ground stations within each zone and they are transmitting in a packet-switched time division multiple access (TDMA) mode. All packets are of fixed length, each requiring one time slot for transmission.

Multiple access in these systems is conveniently viewed at two levels. First is the problem of organizing access from all stations within one zone, which are contending for the same uplink; we call this the station access problem. Second, there is the problem of setting up the satellite switch so that, the packets arriving on the uplinks are switched to the appropriate destination zone downlinks;

this is the switch assignment problem.


The role of the satellite in facilitating station access depends on the intra-zone ground connections. Many situations could exist, but in our case, which is the simplest one, all stations operate independently, so that any contention among ground stations within a zone must be resolved through control via the satellite. Each station transmits to the satellite via the uplink frequency of its zone.

The degree of onboard processing available in the satellite determines the role it can play in both station access and switch assignment.

Figure 10 shows a simplified conceptual model of the system under consideration. All those boxes represent the space segment of the system.

### 3.3 SYSTEM PROTOCOL

Throughout this chapter, we assume the entire area covered by the satellite is divided into  $N$  spatially disjoint spot beam zones. Let  $M$  denote the number of transponders provided by the satellite system. For practical interest, we assume  $M < N$ .



Each beam zone is served by one uplink and possibly several downlink channels. The reason for adopting multiple downlink transmissions is to allow the possibility of simultaneous service of several transponders to the same zone. This would be needed when the traffic on the uplinks is mostly bound for a specific beam zone. Only one uplink channel is used for each zone. The idea of using multiuplinks arises mainly from the need to reduce the contention on the uplink. This problem is now solved since all the area is divided into non-overlapping beam zones. One single uplink channel per beam zone is good enough.

The time axis of each channel is sliced into slots of seconds each representing the length of one packet. The uplink channel is operated in accordance with the slotted ALOHA protocol.

The service provided by a transponder is governed by a TDMA frame. Each transponder can have its own frame structure. A TDMA frame consists of slots each capable of handling the transmission of one packet. Blank slots while a transponder switches from one zone to another may exist in a TDMA frame. We use  $t_r$ , expressed in the number of slots, to denote the length of the transition period. Sometimes the transition period could be ignored, i.e.  $t_r=0$ . Let  $FL_i$  be the frame length of the  $i$ th transponder. Figure 11 shows an example of frame structures of a three beam satellite with two transponders [1]. Each number represents the downlink zone to which the slot is being assigned, while the shaded slot represents a

transition period of 1. The frame length of transponder 1 is 5, while FL2 is 4. The common period between them is the smallest common multiple which is 20. It is easy to see that in such common period, there are several slots during which zone 1 is serviced simultaneously by the two transponders. Therefore, we have assumed two downlink channels for zone 1.

Given the frame structure of the transponders, we can easily derive the frame structure of each zone. Not to mention we have  $N$  such frames. The numbers in the slots could vary between 0 and  $M$ , where 0 represents that the corresponding zone is blocked from service while  $M$  means that all transponders are offering service to the zone during the time slot.

In figure 12, the frame structure of each zone is shown. A zero indicates that the corresponding zone is blocked from downlink service due to each transponder either being busy with some other zone or undergoing a transition period. Similarly, a 2 in the frame structure of zone 1 indicates that during the slot, zone 1 receives downlink service from both transponders. Therefore, two downlink channels are required in that slot.

In other words, as long as the frame structure of each transponder is given, the frame structure and the frame length of each zone can then be obtained accordingly. We assume all uplink channels are completely synchronized in slots.

### 3.3.1 Protocol Formulation [1]

The system protocol can be stated as follows:

Any station with a newly arrived packet ready for transmission, immediately transmits that packet at the beginning of the next slot via the uplink of its zone, since it is operating according to the slotted ALOHA protocol. It then waits a while to determine if a retransmission is needed. When a retransmission is required, the station reschedules the transmission after a randomized delay which is uniform on  $[1, \dots, K1]$ .

If the packet transmitted on the uplink turned out to be successful or did not suffer a collision, the satellite processor at the beginning of each slot picks out from among those successful packets just arrived from the uplinks the ones which are scheduled for downlink transmission during the current slot, and the microwave switch immediately relays these packets to their corresponding transponders. If the number of successful packets which have the same zone as their common destination exceeds the total number of transponders available for that zone in that slot, then the satellite processor randomly selects as many packets as the number of transponders available for that zone and the rest are assumed to be lost or destroyed. The satellite processor in figure 10 is

responsible for determining whether a transmission on the uplink has been a success by performing error checking. One important thing to mention is that there is no buffer available on board the processor. All unserved packets will be destroyed.

### 3.2.2 Packet Acknowledgement

Since a packet could have different source and destination zones, and since the broadcast capacity of each downlink channel is limited to one zone only, there exists the issue of packet acknowledgement. A solution making use of the processing capability of the satellite repeater, is as follows: [1]

Each packet created by a ground station, includes  $b$  bits of overhead that indicate the transmission status of the uplink channel corresponding to the destination zone of this packet. At the beginning of each time slot, if there exists a packet to be served by some transponder and to be transmitted to zone 1 in that slot, then the satellite processor writes into this packet the  $b$  status bits of the uplink channel of zone 1. These bits indicate the transmission status of the most recent  $b$  slots on the uplink. Those bits will be grouped in a string of 0's and 1's where a zero indicates a packet has been lost due to a collision or no available transponder to service it, and a 1 indicates a packet which not only succeeded on the uplink but is also picked up by the transponder and

routed to its destination zone. For uniformity all packets use the same  $b$ . The value of  $b$  must be chosen to be the maximum number of consecutive blank slots which exist in the downlink frame structures of all beam zones. For the example shown in figure 12,  $b=4$ .

Via this approach, a station should start monitoring the downlink transmission,  $R$  slots, the round-trip propagation delay, after the packet was transmitted, and only has to wait at most  $b$  slots, to determine whether a retransmission is needed by inspecting the  $b$  status bits of the first packet which appears on the downlink. In case there is no packet to receive downlink service when a scheduled time slot has arrived, the satellite processor can always insert a control packet in that slot to serve the same purpose: This method is beneficial for the following reasons: First, a separate acknowledgement channel is not required. Second, a station does not have to wait long before it can determine whether a retransmission is needed. Third,  $b$  usually is considerably smaller than the packet length; therefore the cost of overhead is negligible.

This operation is done by the processor at the baseband. In other words, packets received on the uplink must be demodulated first and remodulated before they are transmitted on the downlinks.

3.4 THROUGHPUT ANALYSIS [1]

The throughput is defined as the average number of successful packets transmitted per slot. Since the packet size is equivalent to one slot, the maximum throughput that could be achieved is 1.

Throughout the following analysis, we assume that the traffic from zone 1, constitutes a Poisson process with mean rate  $G_1$  packets/slot. Before we proceed, we will stipulate the notations which will be used.

$S$  Total throughput

$S_1$  Throughput contribution from zone 1

$S_{1j}$  Throughput contribution from zone 1 to zone  $j$

$r_{1j}$  The probability that a packet generated by zone 1 will have zone  $j$  as destination

$M_{1j}$  Number of transponders available from zone 1 during the  $j$ th slot of a TDMA frame of zone 1

$V_1$  Frame length of zone 1

$P_1$  The probability that a packet succeeds on the uplink channel of zone 1

$x_{1j}$  The probability that  $j$  packets succeeding on the uplink channel per slot, will have zone 1 as their destination

$x_1(z)$  The  $z$  transform of  $x_{1j}$ , i.e.

$$x_{10} + x_{11} z + x_{12} z^2 + \dots + x_{1N} z^N$$

$U(x)$  The unit step function.

The success of a packet from zone 1 to zone  $j$  depends on three factors. First, the packet must succeed on the uplink of zone 1. Second, upon its arrival at the satellite, there must be at least one transponder available for zone  $j$ , supposedly  $j$  is the destination zone. Third, the packet must be picked up by the satellite processor, if, together with this packet, the total number of successful packets heading for zone  $j$  exceeds the total number of transponders available for that zone.

The uplink channel is operated according to the slotted ALOHA protocol. The probability that a packet will succeed on the uplink of zone 1 is:

$$P_1 = G_1 e^{-G_1} \quad (1)$$

The probability that there must be at least one transponder available for zone  $j$  in any randomly selected slot is:

$$\frac{U(u_{j1}) + \dots + U(u_{jv_j})}{V_j} \quad (2)$$

which is in fact:

$$\frac{\# \text{ of slots where a transponder is available}}{\text{total number of slots}}$$

$$U(x) = \begin{cases} 1 & x > 0 \\ 0 & \text{otherwise} \end{cases}$$

In the system under study, we assume that the number of transponders is less than the number of zones. A small chance of having a number of packets heading to zone  $j$  exceeds the number of transponders available for that zone is:

$$\sum_{l=1}^M a_{jl} \left\{ \sum_{k=0}^{l-1} q_{1j}(k) + \sum_{k=l}^{N-1} \frac{l}{k+1} q_{1j}(k) \right\} \quad (3)$$

where  $a_{jl}$  and  $q_{1j}(k)$  are defined as follows. Physically,  $a_{jl}$  represents the probability that  $l$  transponders are in fact available for zone  $j$ , given the condition that there is at least one. Mathematically,  $a_{jl}$  is given by the number of  $u_{jr} = l$ ,  $r=1, \dots, V_j$ , divided by  $U(u_{j1}) + \dots + U(u_{jv_j})$ , i.e.:

$$a_{j\ell} = \frac{\sum_{i=1}^{V_j} ID(\ell, u_{ji})}{\sum_{i=1}^{V_j} U(u_{ji})} \quad (4)$$

where  $ID(\ell, x) = \begin{cases} 1 & \text{if } x = \ell \\ 0 & \text{otherwise} \end{cases}$

$q_{ij}(k)$  represents the probability that, in addition to the packet which succeeded on the uplink of zone  $i$ , there are  $k$  more successful packets heading also for zone  $j$  in the same slot. Mathematically,  $q_{ij}(k)$  equals the coefficient of  $z^k$  in:

$$\frac{X_j(z)}{P_{ij}r_{ij}z + (1 - P_{ij}r_{ij})}$$

where  $X_j(z)$  is:

$$X_j(z) = \prod_{i=1}^N [P_{ij}r_{ij}z + (1 - P_{ij}r_{ij})], \quad i=1, \dots, N$$

Therefore,  $q_{ij}(k)$  is:

$$q_{ij}(k) = \frac{1}{k!} \frac{d^k}{dz^k} \left[ \prod_{\substack{i=1 \\ i \neq j}}^N [P_{ij}r_{ij}z + (1 - P_{ij}r_{ij})] \right] \quad (5)$$

$$z = 0$$

by differentiating  $k$  times with respect to  $Z$ , we obtain:

$$q_{ij}(k) = \frac{1}{k!} \sum_{\substack{\ell=1 \\ \ell \neq i}}^N [P_{\ell} r_{\ell j} [ \sum_{\substack{m=1 \\ m \neq \ell \\ m \neq i}}^N P_m r_{mj} \dots \sum_{\substack{s=1 \\ s \neq \ell \\ s \neq i}}^N P_s r_{sj} \dots \sum_{\substack{t=1 \\ t \neq \ell \\ t \neq i}}^N P_t r_{tj} Z + (1 - P_t r_{tj}) ] \dots ]$$

The throughput equation is formulated as follows:

$$S = \sum_{j=1}^N \frac{P_i r_{ij} U(M_{j1}) + \dots + U(M_{jv_j})}{v_j} \left\{ \sum_{\ell=1}^M a_{j\ell} \left[ \sum_{k=0}^{\ell-1} q_{ij}(k) + \sum_{k=\ell}^{N-1} \frac{\ell}{k+1} q_{ij}(k) \right] \right\} \quad (6)$$

The throughput contribution from zone  $i$  is:

$$S_i = \sum_{j=1}^N S_{ij} \quad (7)$$

The total throughput is therefore:

$$S = \sum_{i=1}^N S_i \quad (8)$$

Several plots of the total throughput vs the total arrival rate are shown in figures 13 and 14.

3.5 DELAY ANALYSIS [1]

The following notations with their corresponding definitions will be used in analyzing the average packet delay of the system:

- $D_1$  Average packet delay for packets generated by users in zone 1.
- $NI_1$  The number of idle subframes in the equivalent TDMA frame of zone 1. Here an idle subframe represents a subperiod of maximal length of the equivalent TDMA frame in which no transponder is available.
- $I_{1j}$  The length of the  $j$ th idle subframe in the TDMA frame of zone 1.
- $R$  The round trip propagation delay measured in packet slots:

The delay is the time elapsed between the transmission of a packet and the reception of its acknowledgement by the sender. The round-trip delay and the average time a station has to wait before retransmission is included in the delay expression.

Therefore:

$$D_i = (\text{average number of retransmissions}) \times (\text{delay by each retransmission}) + (\text{delay by the successful transmission}).$$

In section 3.2 we elaborated on the issue of packet acknowledgement. This factor is of extreme importance in calculating the packet delay. We remind that, each packet created by any ground station should include  $b$  bits of overheads in which the satellite processor will write the transmission status on the uplink channel corresponding to the destination zone. The value of  $b$  must be chosen to be the maximum number of consecutive blank slots which exist in the downlink frame structures of all beam zones. Mathematically,  $b$  can be expressed by:

$$B = \text{MAX} (I_{1l})$$

$$i=1, \dots, N$$

$$l=1, \dots, NI_1$$

Therefore, in addition to the round trip delay, a station has to wait at most  $b$  slots to determine whether a retransmission is needed.

We will now find the average number of slots a station has to wait before scheduling retransmission. In the TDMA frame of zone  $i$ , there exist  $NI_1$  idle subframes with different lengths  $I_{1l}$ .

$$\begin{aligned}
 I_{11} &= l_1 \\
 I_{12} &= l_2 \\
 &\vdots \\
 I_{1NI_1} &= l_{NI_1}
 \end{aligned}$$

We group idle subframes in order of length. For simplicity, assume  $l_1 < l_2 < \dots < l_{NI_1}$

The probability of waiting one slot before finding a free transponder is:

$$\frac{\text{Number of idle subframes}}{\text{frame length}} = \frac{NI_1}{V_1}$$

The probability of waiting  $K$  slots before finding a free transponder is:

$$\frac{\text{Number of idle subframes whose length} > K}{V_1} = P_K$$

The average number of slots that one has to wait is:

$$\sum_K K P_K = \frac{1}{V_1} \sum_{l=1}^{NI_1} \sum_{K=1}^{l-1} K$$

The average number of slots a packet has to wait before knowing if a retransmission is needed, is:

$$\frac{1}{V_1} \sum_{i=1}^{NI_1} \frac{1}{2} I_{i1} (I_{i1} + 1) \quad (9)$$

From the protocol definition, the station reschedules the retransmission after a randomized delay which is uniform on  $(1, \dots, k_1)$ . Since this is a uniform distribution with elements each occurring with probability  $1/k_1$ , the average number of slots a station has to wait before rescheduling retransmission is:

$$\frac{1}{k_1} \sum_{i=1}^{k_1} i = \frac{k_1 + 1}{2}$$

Therefore, the delay introduced by a retransmission is [1]:

$$R + 1 + \frac{k_1 + 1}{2} + \sum_{i=1}^{NI_1} \frac{I_{i1} (I_{i1} + 1)}{2V_1} \quad (10)$$

The 1 in the equation stands for one slot taken originally to transmit the packet.

### 3.5.1 Average Number of Retransmissions

We say a packet is successful if:

- 1 - It survives on the uplink,
- 2 - There is a transponder available, and
- 3 - The packet is picked up by the transponder.

Let  $P_1$  equal the probability of survival on the uplink, and  $P_2$  the probability of a transponder available and  $P_3$  the probability that the processor will pick up the transmitted packet. The probability of failure is:

$$1 - P_1 + P_1(1-P_2) + P_1P_2(1-P_3)$$

which is equal to:

$$1 - P_1P_2P_3$$

Since  $S_{ij} = P_1P_2P_3$ , therefore the probability of failure is:

$$(1 - S_{ij})$$

Suppose, we are transmitting a packet from zone i to zone j; the probability that the operation will be completed in one transmission is:

$$1 - (S_{ij} G_{ij} r_{ij})$$

where  $G_{ij} r_{ij}$  represents the fraction of the load directed from zone i to zone j.

$$P\{2 \text{ transmission}\} = (1 - S_{ij}) G_{ij} r_{ij} S_{ij}$$

$$P\{k \text{ transmission}\} = (1 - S_{ij})^{k-1} G_{ij} r_{ij} S_{ij}$$

The average number of retransmission is:

$$\sum_{k=1}^{\infty} k P_k - 1 = \frac{G_{ij} r_{ij}}{S_{ij}} - 1 \quad (11)$$

### 3.5.2 The Total Delay Equation

The delay introduced by all retransmission is:

The total delay in zone  $i$  is the delay introduced by retransmissions added to the delay by a successful transmission. Therefore,  $D_i$  is:

$$D_i = R + 1 + D_R \quad (12)$$

The average packet delay is:

$$D = \sum_{i=1}^N \frac{S_i}{S} D_i \quad (13)$$

In figure 15, the throughput delay characteristic is displayed for different slot assignments.

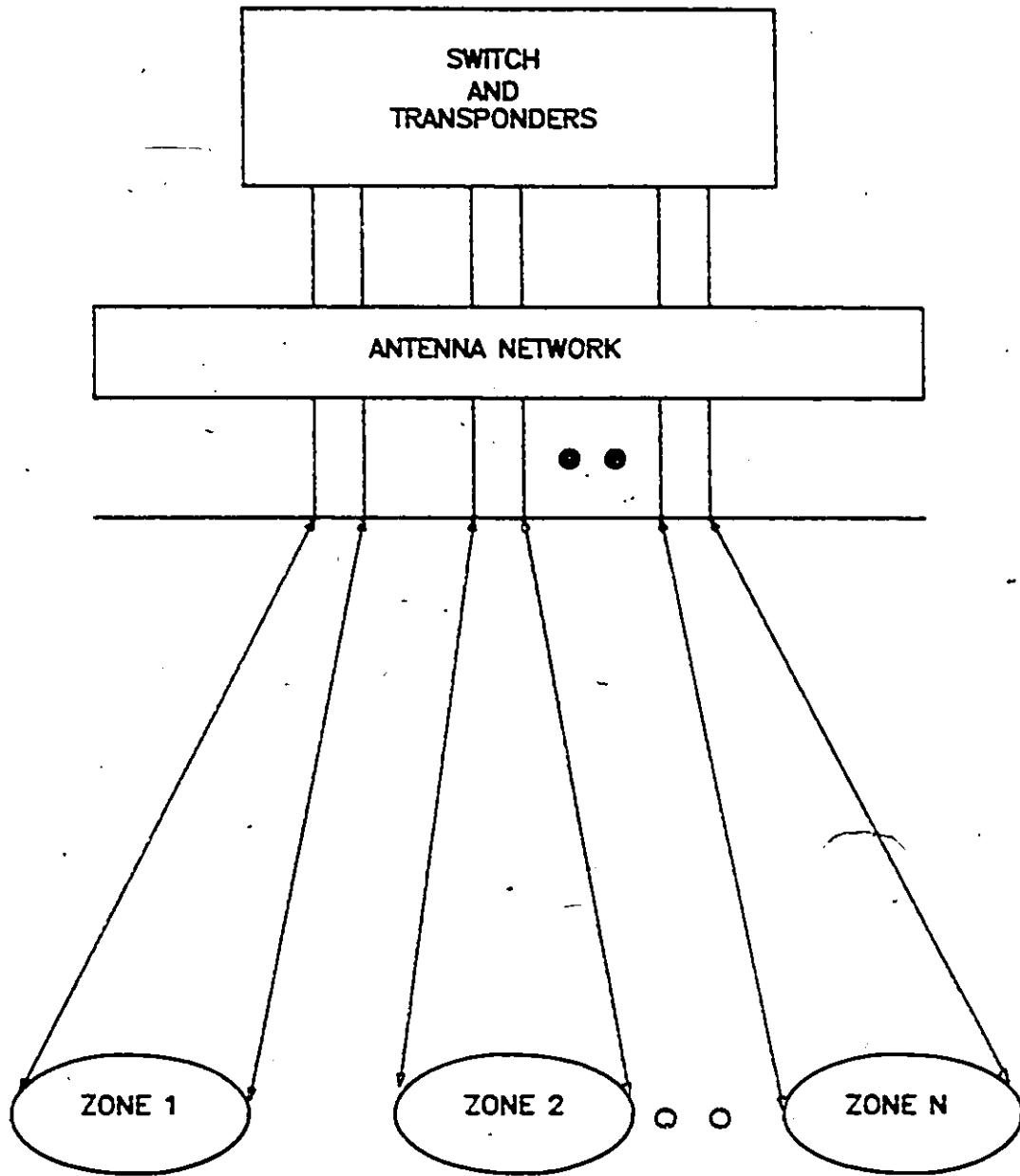


Figure 9 : System configuration.

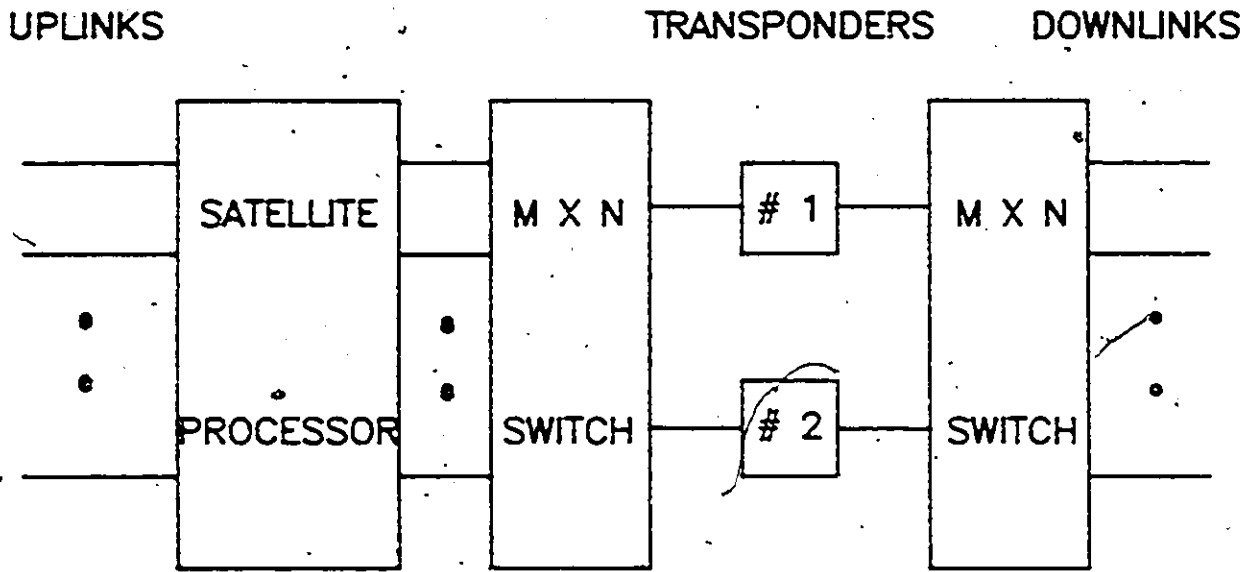


Figure 10 : A simplified conceptual model of the system.

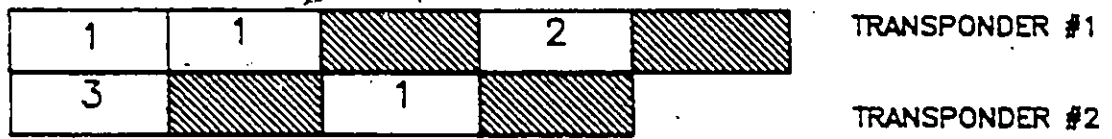


Figure 11 : An example of framed structures with  $M=2$  and  $N=3$ .

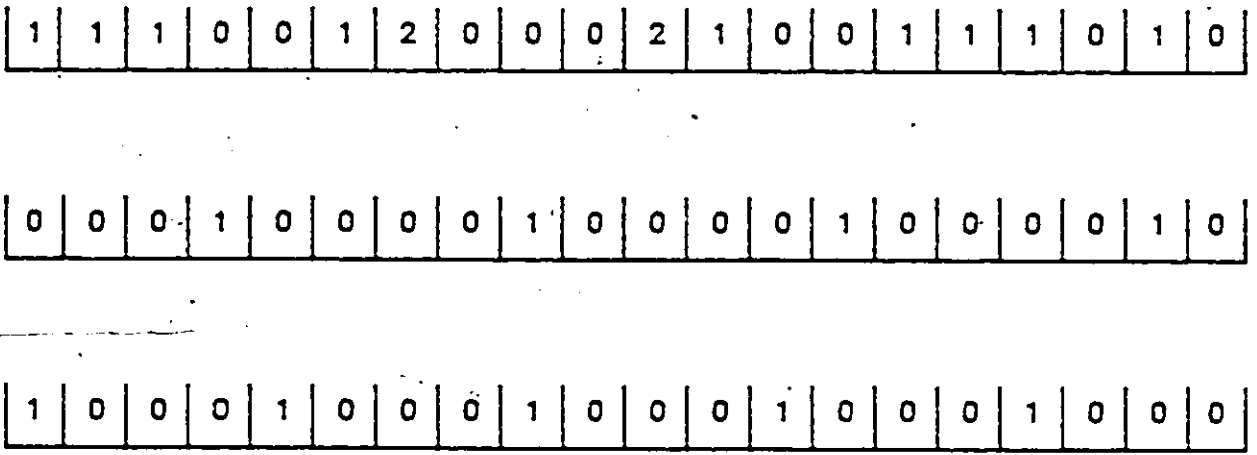


Figure 12 : The TDMA frame structure of each zone .

Figure 13: Channel throughput vs total channel load.

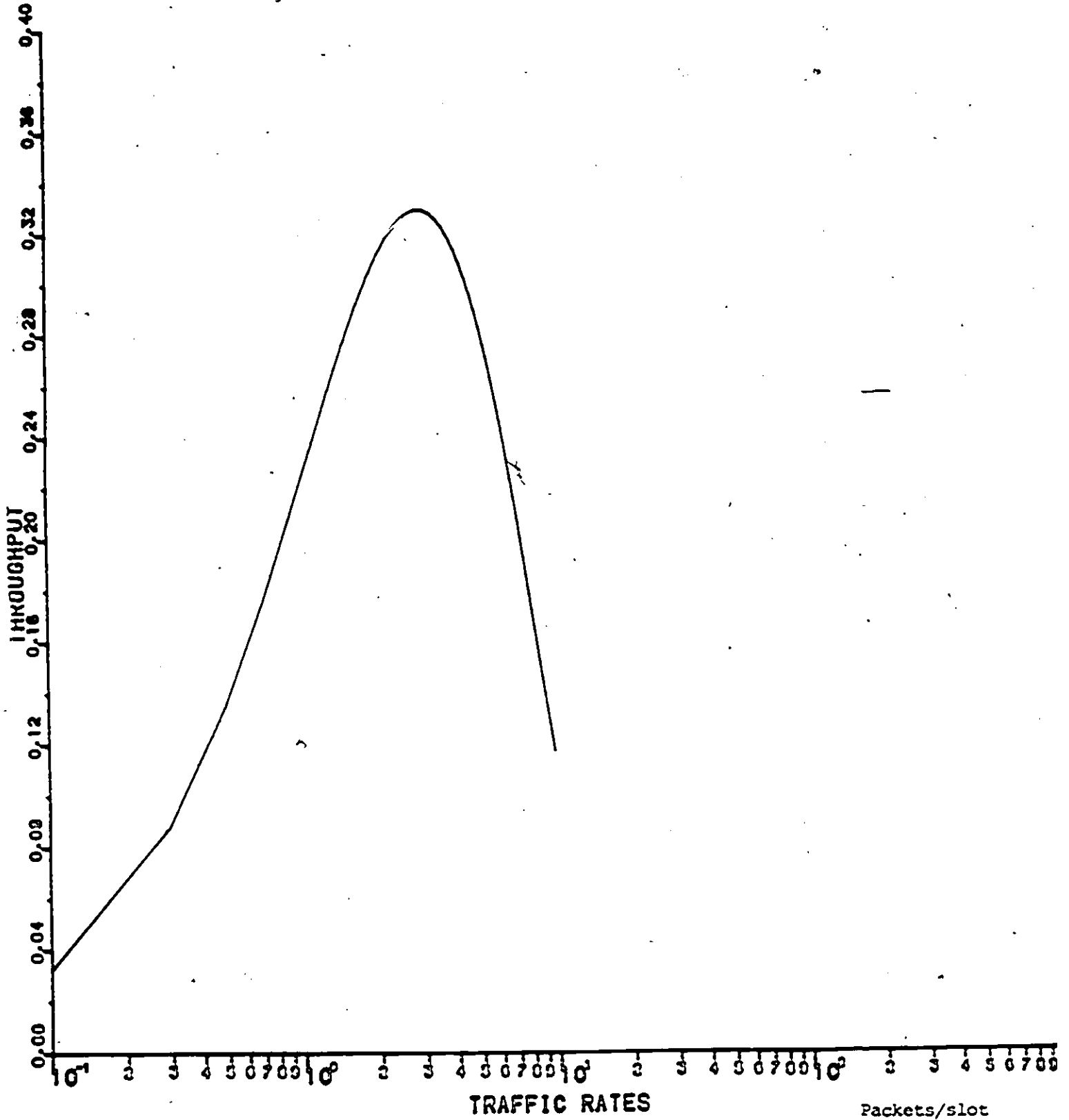


Figure 14: Channel throughput vs total channel load.

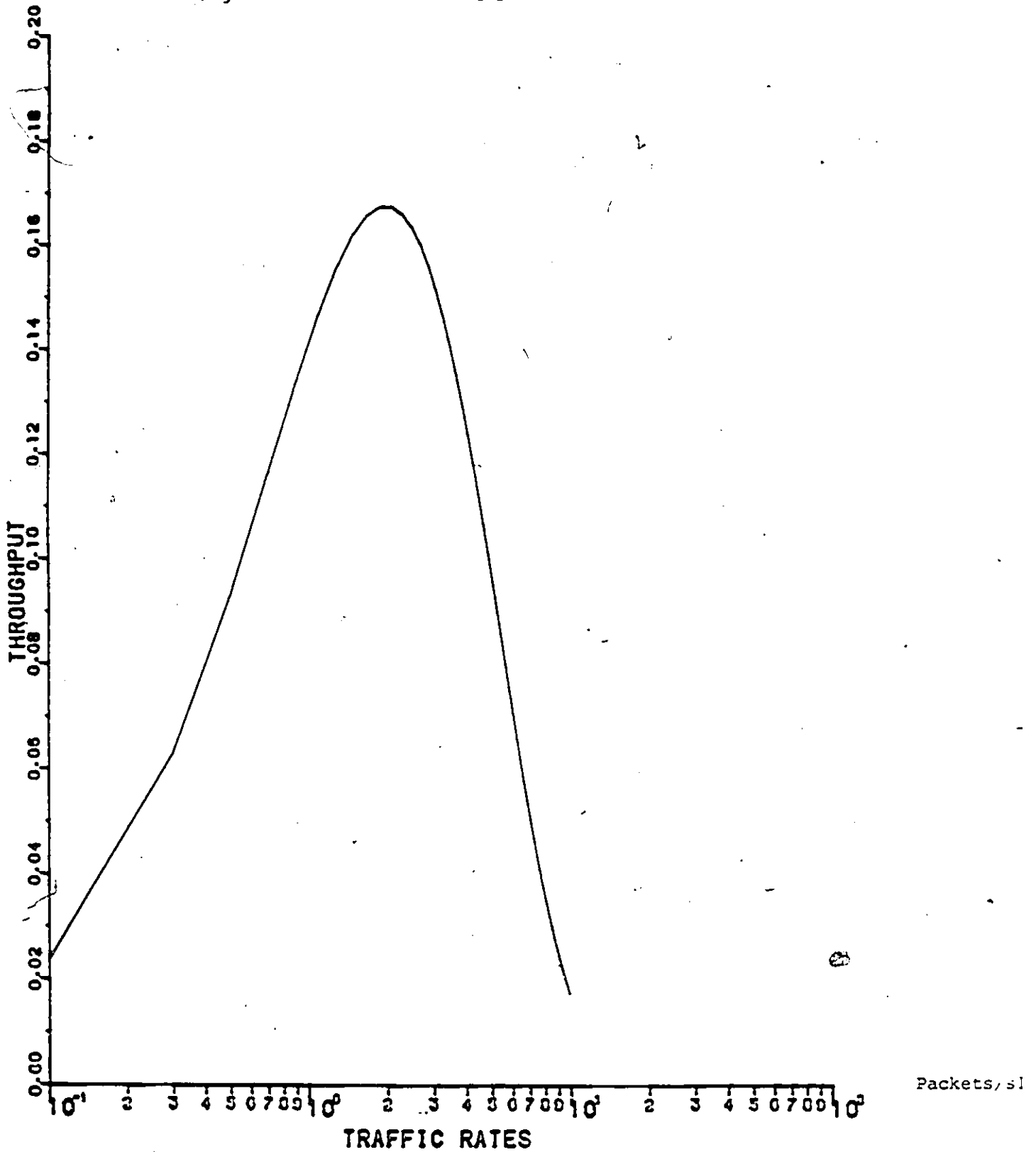
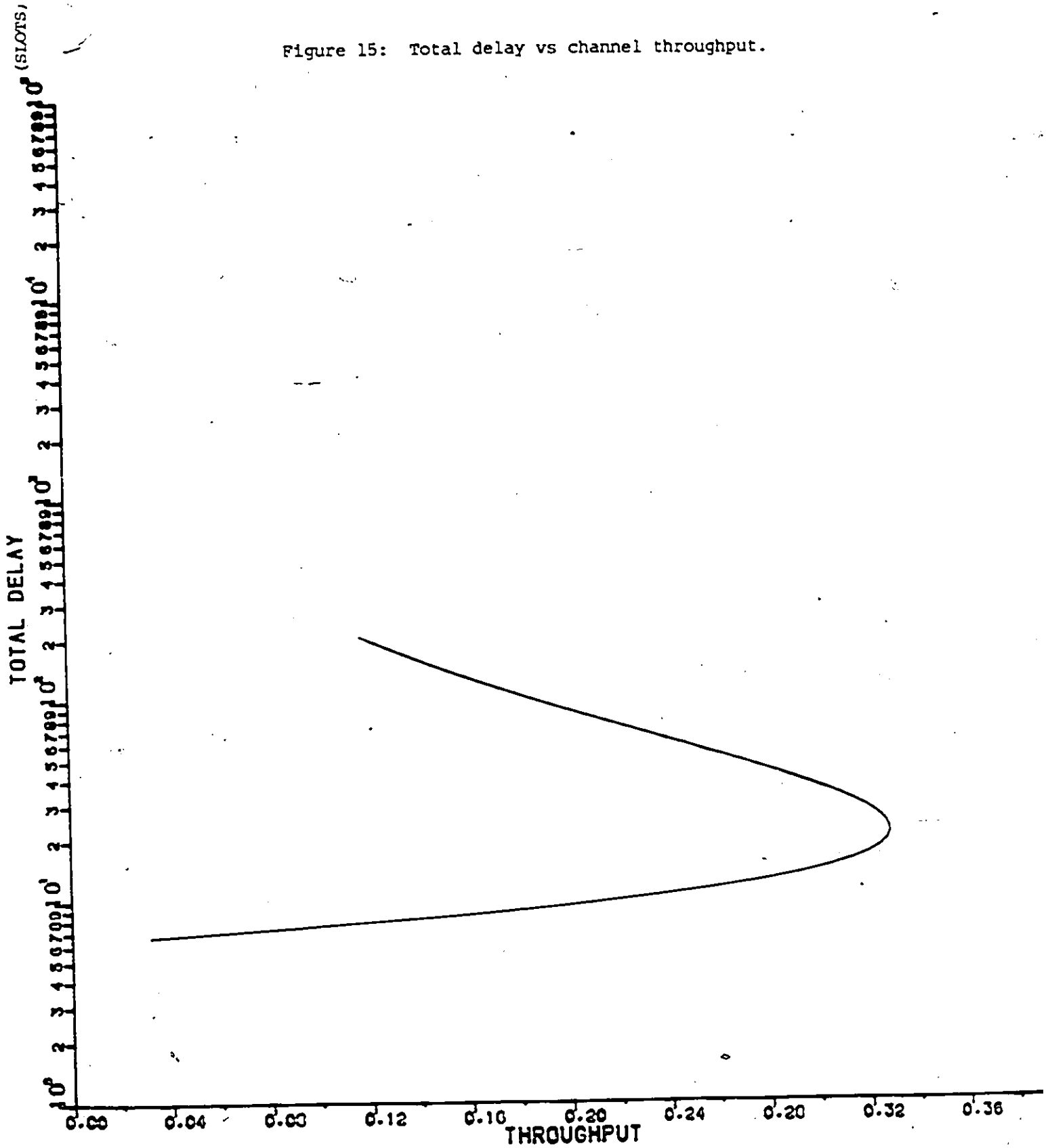


Figure 15: Total delay vs channel throughput.



Chapter IV  
SYSTEM OPTIMIZATION

4.1 MAXIMIZATION OF THE THROUGHPUT

In the previous chapter, the throughput equation was found.

$$S = \sum_{i=1}^N \sum_{j=1}^N P_{ij} r_{ij} \frac{U(\lambda_{j1}) + \dots + U(\lambda_{jM})}{V_j} \left\{ \sum_{l=1}^M a_{jl} \left[ \sum_{k=0}^{l-1} q_{ij}(k) + \sum_{k=l}^{N-1} \frac{l}{k+1} q_{ij}(k) \right] \right\}$$

The variables involved in this equation are:  $N$ , the number of zones,  $M$ , the number of transponders, the traffic rates from all zones, the routing matrix and the transponder availability in each zone.

We shall assume that the number of transponders and the number of zones is given along with the traffic rates. The question now is: what is the slot assignment that would yield a maximum throughput, with the condition that  $N$  and  $M$  and the traffic rates remain constant. For this purpose we define new variables as follows

$z_{lj}$ :

$z_{lj}$  is the number of slots in the TDMA frame for zone  $j$ , where in fact  $l$  transponders are available.

We will try to express the throughput equation as a function of these variables and in this way, the optimization would become simple.

The average number of busy slots in the TDMA frame of zone  $j$  is:

$$\frac{U(\mu_{j1}) + \dots + U(\mu_{jv_j})}{v_j}$$

which was defined in the previous chapter. This mathematical expression could be evaluated in terms of  $z_{lj}$ .

$$\frac{U(\mu_{j1}) + \dots + U(\mu_{jv_j})}{v_j} = \frac{z_{1j} + z_{2j} + \dots + z_{Mj}}{v_j} = \frac{\sum_{l=1}^M z_{lj}}{v_j} \quad (14)$$

The probability that there is  $l$  transponder available for zone  $j$  with the condition that there is at least one is  $a_{jl}$ ;

$$a_{jl} = \frac{\sum_{i=1}^v j I D(l; u_{ji})}{\sum_{i=1}^v j u(\mu_{ji})} = \frac{z_{lj}}{\sum_{l=1}^M z_{lj}} \quad (15)$$

The above substitutions would yield a linear throughput equation in terms of  $z_{lj}$ .

$$S_{1j} = \frac{P_{1r} v_j}{v_j} \left\{ \sum_{l=1}^M z_{lj} \left[ \sum_{k=0}^{l-1} q_{1j}(k) + \sum_{k=l}^{N-1} \frac{l}{k+1} q_{1j}(k) \right] \right\} \quad (16)$$

The number of unknowns in the equation is  $N \times M$ . Using linear programming, we can maximize the throughput subject to some constraints. Obviously, by choosing a fixed TDMA frame length for all zones would make the problem simpler. The frame length will be unique for  $j=1, \dots, N$ .

The total number of constraints is  $M + N$ ;  $M$  inequality constraints and  $N$  equality constraints. Those are defined next.

$$(a) \sum_{j=1}^N z_{lj} M_j \leq V$$

This constraint means that the total number of slots in the TDMA frames of all  $N$  zones, where we assign  $M$  transponders should be less than or equal to the frame length. If in any slot, all  $M$  transponders are assigned to zone 1, then in the same time slot no service will be offered to the other zones.

$$(b) \sum_{l=0}^M z_{lj} = V \quad j = 1, 2, \dots, N$$

This means that the total number of slots where zero and one  
 ....., and M transponders are available is equal to the frame length.

$$(c) \sum_{j=1}^N \sum_{l=1}^{M-1} z_{lj} \leq V - \sum_{j=1}^N z_{Mj}$$

This means that transponders can be assigned in slots where not  
 all transponders are assigned to one zone. This constraint is  
 necessary to make sure that the total number of transponders in  
 a given slot will not exceed M.

$$(d) \sum_{j=1}^N z_{1j} \leq V - \sum_{j=1}^N z_{Mj}$$

This constraint is necessary for the same purpose as above

$$(e) \sum_{j=1}^N z_{2j} \leq V - \sum_{j=1}^N \sum_{l=M-1}^M z_{lj}$$

Since the maximum number of transponders that could be  
 assigned in a time slot is M, slots with 2 transponders  
 assigned should not be coincident with slots where (M-1) or M  
 transponders are assigned.

$$(f) \sum_{j=1}^N z_{lj} \leq V - \sum_{j=1}^N \sum_{k=M-1}^{M-1} z_{kj}$$

This is the general form from which,  $M$  constraints could be derived, the constraint in part (e) is a special form of this one.

Therefore, given the number of zones  $N$ , the number of transponders  $M$ , the traffic rates and the routing matrix, we can maximize the throughput by solving the linear programming problem via the revised simplex algorithm. In the last section of this chapter, various examples are given to demonstrate this optimization method.

#### 4.2 MINIMIZATION OF THE AVERAGE PACKET DELAY

An important observation is that the order in which the slots are arranged does not affect the throughput, but has a considerable influence on the average packet delay. The idea is to minimize the packet delay, given the conditions which maximizes the total system throughput.

The delay in zone  $i$  is:

$$D_i = R + 1 + \sum_{j=1}^N F_{1j} \left( \frac{G_{1j}}{S_{1j}} - 1 \right) \left( R + 1 + \frac{K + 1}{2} + \sum_{l=1}^{NI_1} \frac{I_{1l} (I_{1l} + 1)}{2v_1} \right) \quad (17)$$

where  $R$  is the round-trip propagation delay and,  $K$  the average randomized retransmission delay.

Given  $Z_{ij}$  for  $i=1, \dots, M$  and  $j=1, \dots, N$ , the problem is to create an algorithm which optimally arranges slot contents. In other words, find  $I_{1i}$  and  $NI_1$  for all  $i$ 's, to minimize the average delay.

Let  $R + 1 = K_1$ , and,  $R + 1 + (K - 1)/2 = K'$ ;

Let  $K_{ij} = G_i r_{ij}$

Therefore,  $D_i$  is:

$$D_i + k_1 + \sum_{j=1}^N \left( \frac{k_{ij}}{S_{ij}} - r_{ij} \right) \left( k' + \sum_{l=1}^{NI_1} \frac{I_{1l}(I_{1l} + 1)}{2V_1} \right)$$

$$D = \frac{1}{S} \sum_{i=1}^N S_i D_i$$

The minimization of  $D$  is the same as minimizing

$$\frac{1}{S} \sum_{i=1}^N S_i D_i$$

$$S_i D_i = k_1 S_i + (k' S_i + S_i \sum_{l=1}^{NI_1} \frac{I_{1l}(I_{1l} + 1)}{2V_1} \sum_{j=1}^N \left( \frac{k_{ij}}{S_{ij}} - r_{ij} \right))$$

$$= \left[ k_1 + k' \sum_{j=1}^N \left( \frac{k_{ij}}{S_{ij}} - r_{ij} \right) \right] S_i + S_i \sum_{j=1}^N \left( \frac{k_{ij}}{S_{ij}} - r_{ij} \right) \sum_{l=1}^{NI_1} \frac{I_{1l}(I_{1l} + 1)}{2V_1} \quad (18)$$

$z_{ij}$  is given, thus,  $S_{ij}$ ,  $S_1$ , and  $S$  are all constant.

Let

$$x_1 = S_1 \sum_{j=1}^N \left( \frac{k_{1j}}{S_{1j}} - r_{1j} \right)$$

$$y_1 = \left[ k_1 + k' \sum_{j=1}^N \left( \frac{k_{1j}}{S_{1j}} - r_{1j} \right) \right] S_1$$

then,

$$S_1 D_1 = y_1 + x_1 \frac{\sum_{q=1}^{N_1} I_{1q} (I_{1q} + 1)}{2V_1}$$

We know that

$$\sum_{q=1}^{N_1} I_{1q} = z_{01}$$

which is the number of idle slots in the frame.

Therefore,

$$D = \frac{1}{S} \left\{ \sum_{i=1}^N y_i + \frac{1}{2V} \sum_{i=1}^N x_i \sum_{q=1}^{N_1} I_{1q}^2 + \frac{1}{2V} \sum_{i=1}^N x_i z_{01} \right\} \quad (19)$$

The delay equation is a non-linear equation in  $I_{i\ell}$  with

$$1 < i < N, \quad 1 < \ell < NI_1;$$

The problem is now easier to deal with, for the reason that instead of minimizing the delay equation as a whole, we need to minimize the expression:

$$\sum_{i=1}^N X_i \sum_{\ell=1}^{NI_1} I_{i\ell}^2 \quad (20)$$

#### 4.2.1 The Lagrange Multiplier Solution

Let us find the optimal solution using the Lagrange multiplier analysis. We define a vector of Lagrange multipliers

$$\lambda = [\lambda_1, \lambda_2, \dots, \lambda_N]$$

The function to minimize is:

$$f = \sum_{i=1}^N f_i$$

where

$$f_i = k_{i1}I_{i1}^2 + k_{i2}I_{i2}^2 + \dots + k_{iNI_1}I_{iNI_1}^2$$

with the  $N$  equality constraints:

$$\sum_{k=1}^{NI_1} I_{1k} = z_{01} \quad i = 1, 2, \dots, N$$

or,

$$\sum_{k=1}^{NI_1} I_{1k} - z_{01} = 0$$

Let  $H$  be:

$$H = f + \lambda X$$

$$X = \begin{bmatrix} \sum_{k=1}^{NI_1} I_{1k} - z_{01} \\ \sum_{k=1}^{NI_2} I_{2k} - z_{02} \\ \vdots \\ \sum_{k=1}^{NI_N} I_{Nk} - z_{0N} \end{bmatrix}$$

To have a minimum all partial derivatives should be zero.

$$\frac{\partial H}{\partial I_{1k}} = 2k_1 I_{1k} + \lambda_1 = 0 \text{ for all } 1\text{'s}$$

Therefore,

$$I_{i\ell} = -\lambda_i / 2k_i \quad ; \quad (21)$$

Applying the value of  $I_{i\ell}$  in the constraint equation,

$$z_{0i} = \sum_{\ell=1}^{NI_i} I_{i\ell} = \sum_{\ell=1}^{NI_i} \frac{-\lambda_i}{2k_i} = \frac{-NI_i \lambda_i}{2k_i}$$

The optimal value of  $I_{i\ell}$  is:

$$I_{i\ell} = z_{0i} / NI_i \quad (22)$$

which is independent of  $\ell$ .

To prove that the optimal value of  $I_{i\ell}$  yields a minimum, let us find the second derivative of the function H.

$$\frac{\partial^2 H}{\partial I_{i\ell}^2} = 2k_i > 0$$

Since the second derivative is positive, the critical point we have found gives indeed an absolute minimum of the function H.

From the above result, we can conclude that all idle subframes in the TDMA frame of zone  $i$  should have the same length, to guaranty a minimum delay. The number of idle subframes  $NI_i$  in the TDMA frame

structure of zone i is:

$$NI_1 = \text{MIN} (z_{01}, \sum_{l=1}^M z_{l1})$$

#### 4.2.2 The Optimized Delay Equation

The average packet delay equation, after applying the previous analysis, becomes:

$$D = \frac{1}{S} \left\{ \sum_{i=1}^N y_i + \frac{1}{2v} \sum_{i=1}^N x_i z_{0i} + \frac{1}{2v} \sum_{i=1}^N x_i \sum_{l=1}^{NI_1} \frac{(z_{0i})^2}{NI_1} \right\} \quad (23)$$

with

$$NI_1 = \text{MIN} (z_{01}, \sum_{l=1}^M z_{l1}) \quad (24)$$

We should try as much as possible to have many idle subframes in order to minimize the average packet delay.

For this reason, we will create as many as possible idle subframes in order to reduce the delay, since it is proportional to the sum of the squares of idle subframes lengths.

#### 4.3 OPTIMIZATION ALGORITHM

In the previous sections of this chapter, we applied an optimization procedure to obtain a maximum throughput with minimum delay. Usually, in a multibeam system, the number of zones is larger than the number of transponders. A realistic system includes 5 transponders and serves 10 beam zones. From this point-of-view arises the idea of organizing TDMA zone frames. As the number of transponders increases, the idea of defining a suitable slot assignment becomes more complex. Before coming to a conclusion that will yield the optimization algorithm, we state few definitions.

Definition:

Two slot assignments are called dependent if they yield the same average packet delay. It could be that those two frames do not look alike, but the delay depends upon the number of idle subframes and their lengths.

Case 1: System with one transponder (M=1).Proposition I:

Given a TDMA frame of length  $V$  bits, the number of configurations of slot assignments which could be generated is  $2^V$ . That frame could have in its slots either one's or zero's. Let  $K$  be the number of one's in the frame; therefore, the number of combinations with  $K$  one's is:

$$C_V^k = \frac{V!}{k! (V-k)!} \quad (25)$$

and the number of independent slot assignments is:

$$\frac{C_V^k}{V} = \frac{(V-1)!}{k! (V-k)!} \quad (26)$$

Since the frame is periodic with period  $V$  (i.e. all bits are repeated every  $V$  time slots), by rotating those frames left and right, one can get identical frames.

#### 4.3.1 Procedure to find all Independent Assignments

- given the frame length  $V$ ;
- given  $Z_{lj}$  ;  $l=0,1$  ;  $j = 1,2,\dots,N$

Step 1: Find the number of independent slot assignments.

Step 2: Group all one's in the most significant bit positions.

Step 3: Shift the LSB of the one's to the right one bit at a time.

Step 4: Repeat step 3,  $(V-K-1)$  times.

Step 5: Repeat step 2.

Step 6: Shift two one's to the right and repeat step 3. Each time you accomplish a shift, you obtain a frame configuration, all these configurations are independent frames. Repeat this procedure and stop when the number of configurations is equal to the number obtained in step 1.

#### Example:

Frame length = 9 slots,  $K=4$

Number of independent frames = 14;

Those frames are:

```

1 1 1 1 0 0 0 0 0
1 1 1 0 1 0 0 0 0
1 1 1 0 0 1 0 0 0
1 1 1 0 0 0 1 0 0
1 1 1 0 0 0 0 1 0
1 1 0 1 1 0 0 0 0
1 1 0 1 0 1 0 0 0
1 1 0 1 0 0 1 0 0
1 1 0 1 0 0 0 1 0
1 1 0 0 1 1 0 0 0
1 1 0 0 1 0 1 0 0
1 1 0 0 1 0 0 1 0
1 0 1 0 1 1 0 0 0
1 0 1 0 1 0 1 0 0

```

Case 2: System with Multiple Transponders

Proposition 2:

Given a frame of length  $V$ , where the number of zero's in the frame is  $K$ ; the total number of independent assignments is:

$$\frac{(V - K)(V - K + 1)(V - K + 2)}{6} \quad (27)$$

Procedure for finding all independent assignments:

- Given the frame length  $V$ ;
- Given  $Z_{\ell i}$  ;  $\ell = 0, 1, \dots, M$  ;  $i = 1, 2, \dots, N$

Step 1: Find the number of independent slot assignments.

Step 2: Place all zero's in the LSB positions.

Step 3: Shift to the left the most significant zero, one at a time, until it is in the  $(V-1)$  bit position.

Step 4: Repeat step 2 and shift to the left two zero's which are in the MSB positions.

Step 5: Repeat step 4 until the number of independent slot assignments, given by step 1, is obtained.

The average packet delay is proportional to the square value of idle subframes lengths. Therefore, by choosing frames with short idle subframes, we would guaranty an optimal delay.

Example:

Frame length = 7 and  $K = 3$ ;

The number of independent frames = 20;

Those frames are:

```

2 2 1 1 0 0 0
2 2 1 0 1 0 0
2 2 0 1 1 0 0
2 0 2 1 1 0 0
2 2 1 0 0 1 0
2 2 0 1 0 1 0
2 0 2 1 0 1 0
2 2 0 0 1 1 0
2 0 2 0 1 1 0
2 0 0 2 1 1 0
2 2 1 0 0 0 1
2 2 0 1 0 0 1
2 0 2 1 0 0 1
2 2 0 0 1 0 1
2 0 2 0 1 0 1
2 0 0 2 1 0 1
2 2 0 0 0 1 1
2 0 2 0 0 1 1
2 0 0 2 0 1 1
2 0 0 0 2 1 1

```

A Method For Finding An Optimal TDMA Assignment:

We will present the summary of our optimal TDMA assignment procedure. The following algorithm contains all steps needed to optimize a multibeam system. This algorithm will yield a maximum throughput and a minimum average packet delay.

- Given the number of zones N;
- Given the number of transponders M;
- Given the generation rate of each zone in packet/slot;
- Given the routing matrix from zone i to zone j;

1 - Find  $z_{lj}$  for  $1 < l < M$  and  $1 < j < N$  using the linear programming approach in order to maximize the total throughput.

2 - Find the number of idle subframes for all j, using:

$$NI_1 = \text{MIN}(z_{01}, \sum_{l=1}^M z_{l1})$$

3 - Generate all independent assignments.

4 - Find the lengths of all idle subframes using the Lagrange multiplier method.

5 - Choose the slot assignment that would satisfy conditions 2 and 4.

6 - Having all necessary information, find the average packet delay from the delay equation.

## Chapter V

## CONCLUSION

A Satellite Switched Time Division Multiple Access System (SS/TDMA) with a pool of resources shared by several users was considered here. The protocol used for such a system is easy to implement and requires no detailed measurements of arriving traffic and routing probabilities between users. The protocol was defined and presented according to Chang [1]. The throughput and delay equations were given. The optimization of these system performance measures was studied in detail and an optimization algorithm was finally generated.

To allow use of this analysis and the theoretical results in system of realistic size, an efficient algorithm was presented. From that, commonly considered system performance measures can be determined with some amount of computation. All necessary computer programs are included in this thesis in appendices following this section.

In an actual system design problem, the designer is required to verify that the system under study is similar to the one we have presented, and then find the optimal system parameters numerically. For such optimization it is needed to know the size of the system. What we mean by that is the number of transponders on board the

satellite and the number of users or ground stations to be served by those transponders. We should note that one ground station could carry the traffic of many users which have known traffic rates and routing matrix. After this, based on the signal processing capability of the satellite processor, we should choose a universal frame length for all zones, and by means of linear programming, the transponders are assigned to the zones in a way maximizing the total throughput. Arranging slots is taken care of by the algorithm which minimizes the average packet delay. In the case of changes in system parameters like traffic rates or the routing matrix, the whole procedure has to be repeated and new slot assignments should be generated.

Increasing the number of transponders will enhance the system's performance, but on the other hand, the cost of the system will also increase. The total system cost should be kept in mind to allow us to determine the total number of resources required.

We have not considered the case where a buffer of size  $I$  is introduced in the system. The system performance can be greatly enhanced via the use of sufficiently large buffer and appropriate TDMA frames. For an  $N$ -zone- $M$ -beam system, the system is essentially equivalent to an  $N$ -uplink- $M$ -downlink system with  $L=0$  as far as throughput is concerned. Based on the above observations, a multibeam satellite is more cost-effective than a conventional multiuplink-multidownlink system.

The advantage of using a multibeam system is that fewer channels are needed and there is less consumption of downlink transmitted power. In addition, a multibeam system offers a wide range of operations. However, degradation exists when  $t_r$ , the transition period, cannot be ignored and the multibeam system suffers a slightly longer delay than a multiuplink-multidownlink system.

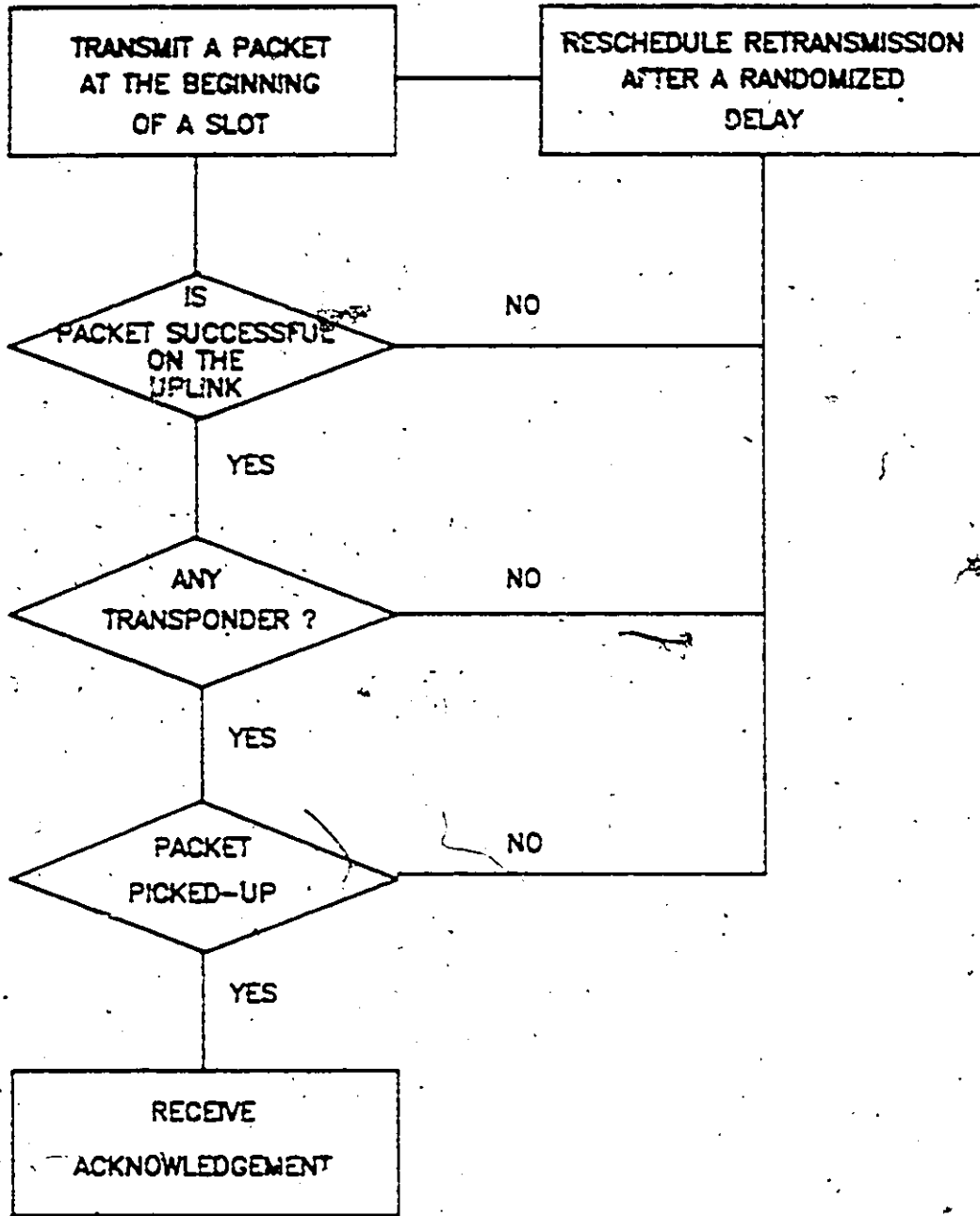
In this thesis, we have assumed the transition overhead  $t_r$  to be an integer number of slots. In practice, if  $t_r$  is less than 1 slot, one could let one transponder undergo exactly one slot of transition in order to maintain a completely synchronized system. However, it is also possible to slice the time axis based on the length of  $t_r$  and operate the system on this basis. Available improvements need to be defined. The use of very fast digital switches could reduce  $t_r$  to a point it would become negligible compared to the time slot.

Finally, we have not addressed the problem of using multiple uplink channels for each zone. In this case, each user in a group could transmit to the satellite as soon as a packet is generated and would not have to route the traffic through a central office which takes care of the uplink transmission. This, indeed, will increase the throughput.

The work should be extended to include the multiuplink concept and the issue of packet prioritization could be studied.

It is hoped that these results will be useful to the designers of SS/TDMA satellite systems.

APPENDIX A  
SYSTEM PROTOCOL ALGORITHM



Appendix B

COMPUTER PROGRAMS

THIS PROGRAM CALCULATES THE THROUGHPUT OF THE SYSTEM.  
THE MAXIMUM NUMBER OF THE ZONES IS 6.

```
REAL P(15), R(15,15), S, AL, AK, SUM, SUM1, SUM2, T(15,15), TH(10), THR
REAL Z(15,15), N
INTEGER I, J, K, L, L1, O
READ N
READ, (P(I), I=1, N)
DO 1 I= 1, N
READ, (R(I, J), J=1, N)
1 READ, M
READ, N
L=1
DO 2 J=1, N
2 READ, (Z(L, J), L=1, M)
I=1
WHILE (L.LE.M) DO
S1=0
K=0
L1=L-1
WHILE (K.LE.L1) DO
O=K+1
CALL QIJ(I, J, N, O, P, R, S)
PRINT, I, J, S
IF (O.EQ.3) S=0.5*S
IF (O.EQ.4) S=S/6
IF (O.EQ.5) S=S/24
IF (O.EQ.6) S=S/120
S1=S1+S
K=K+1
END WHILE
SU 1L=SUM1+Z(L, J)+S1
L=L+1
END WHILE
SUM2=0
L=1
WHILE(L.LE.M) DO
S2=0
K=L
L1=N-1
WHILE (K.LE.L1) DO
O=K+1
CALL QIJ(I, J, N, O, P, R, S)
PRINT, I, J, S
IF(O.EQ.3) S=S/2
IF(O.EQ.4) S=S/6
IF(O.EQ.5) S=S/24
IF(O.EQ.6) S=S/120,
```

```

AL=L
AK=K
S2=S2+S*(AL/(AK+1.))
K=K+1
end while
SUM2=SUM2+Z(L,J)*S2
L=L+1
END WHILE
T(I,J)=SUM1+SUM2)*(P(I)*P(I,J)/V)
J=J+1
END WHILE
I=I+1
END WHILE
THI=0
I=1
WHILE (I.LE.N) DO
J=1
WHILE (J.LE.N) DO
THI=THI+T(I,J)
J=J+1
END WHILE
I=I+1
END WHILE
PRINT,THI
STOP
END

```

```

C
SUBROUTINE QIU(I,J,N,O,P,R,S)
REAL P(15), R(15,15), S,S1,S2,S3,S4,S5,S6,PC,TH(10),T(15,15)
INTEGER I,J,K,N,O,K1,K2,K3,K4,K5,K6
PRINT,J
IF(0.EQ.1)GOTO 10
IF(0.EQ.2)GOTO 20
IF(0.EQ.3)GOTO 30
IF(0.EQ.4)GOTO 40
IF(0.EQ.5)GOTO 50
S1=0
K1=0
WHILE (K1.LE.N) DO
-50 IF(K1.EQ.I)GOTO 11
S2=0
K2=0
IF(0.EQ.5)K1=N+1
WHILE(k2.LE.N) DO
40 IF(K2.EQ.I.OR.K2.EQ.K1)GOTO 12
S3=0
K3=1
IF(0.EQ.4)K1=N+1
IF(0.EQ.4)K2=N+1
WHILE K3.LE.N) DO
30 IF(K3.E).I.OR.K3.EQ.K2.OR.K3.EQ.K1)GOTO 13
S4=0
K4=1
IF(0.EQ.3)K1=N+1
IF(0.EQ.3)K2=N+1

```

```

IF(0.EQ.3)K3=N+1
WHILE (K4.LE.N)DO
IF(K4.EQ.1. OR.K4.EQ.K1.OR.K4.EQ.K2.OR.K4.EQ.K3)GOTO 14
20 S5=0
K5=1
IF(0.EQ.2)K1=N+1
IF(0.EQ.2)K2=N+1
IF(0.EQ.2)K3=N+1
IF(0.EQ.2)K4=N+1
WHILE K5.LE.N)DO
10 IF(K5.EQ.1.OR.K5.EQ.K1.OR.K5.EQ.K2.OR.K5.EQ.K3.OR.K5.EQ.K4)GOTO 15
P0=1
K6=1
IF(0.EQ.1)K1=N+1
IF(0.EQ.1)K2=N+1
IF(0.EQ.1)K3=N+1
IF(0.EQ.1)K4=N+1
IF(0.EQ.1)K5=N+1
WHILE (K6.LE.N)DO
IF(K6.EQ.1.OR.K6.EQ.K1.OR.K6.EQ.K2.OR.K6.EQ.K3)GOTO 16
IF(K6.EQ.K4.OR.K6.EQ.K5)GOTO 16
16 P0=P0*(1.-P(K6)*R(K5,J))
K6=K5+1
END WHILE
IF(0.EQ.1)S=P0
IF(0.EQ.1)GOTO 200
15 S5=S5+P(K5)*R(K5,J)*P0
K5=K5+1
END WHILE
IF(0.EQ.2)S=S5
IF(0.EQ.2)GOTO 200
14 S4=S4+P(K4)*R(K4,J)*S5
K4=K4+1
END WHILE
IF(0.EQ.3)S=S4
IF(0.EQ.3)GOTO 200
13 S3=S3*P(K3)*R(K3,J)*S4
K3=K3+1
END WHILE
IF(0.EQ.4)S=S3
IF(0.EQ.4)GOTO 200
12 S2=S2*P(K2)*R(K2,J)*S3
K2=K2+1
END WHILE
IF(0.EQ.5)S=S2
IF(0.EQ.5)GOTO 200
11 S1=S1*P(K1)*R(K1,J)*S2
K1=K1+1
END WHILE
200 S=S1
RETURN
END

```

PROGRAM TO FIND THE TOTAL THROUGHPUT AND THE AVERAGE PACKET DELAY.

```
REAL A(9,9),B(9,9),Q0(9,9),Q1(9,9),Q2(9,9)
REAL G(5),R(5,5),P(5),V(5),W(5)
REAL S1,S2,S3,B1(10,10),Z(10),D(10)
REAL ID(20,20),SI(20)
REAL MAX,MIN,MAX1
INTEGER NI(10),K,W2,W1,K5,K6
N=3
V1=3
R1=.54
DO 17 I=1,N
G1=.1
WHILE (G1.LE.10.) DO
DO 18 I=1,N
G(I)=G1/N
Z(I)=1
18. CONTINUE
NI(1)=1
NI(2)=2
NI(3)=1
DO 3 I=1,N
K=NI(I)
DO 3 L=1,K
ID(I,L)=(V1-Z(I))/NI(I)
3 CONTINUE
K1=1
DO 2 I=1,N
P(I)=G910*EXP(-G(I))
2 CONTINUE
I=1
WHILE (I.LE.N) DO
J=1
WHILE (J.LE.N) DO
CALL QIJA(I,J,N,P,R,Q0(I,J))
CALL QIJB(I,J,N,Q1(I,J),P,R)
CALL QIJC(I,J,N,P,R,Q2(I,J))
J=J+1
END WHILE
I=I+1
END WHILE
J=1
WHILE (J.LE.N) DO
I=1
WHILE (I.LE.N) DO
IF(N.EQ.2) THEN DO
A(I,J)=(P(I)*R(I,J)/V1)*(Q0(I,J)+.5*Q1(I,J))
ELSE DO
```

```

A(I,J)=(P(I)*R(I,J)/V1)*(Q0(I,J)+.5*Q1(I,J)+.333*Q2(I,J))
END IF
I=I+1
END WHILE
J=J+1
END WHILE
J=1
WHILE(J.LE.N)DO
I=1
W(J)=0
WHILE (I.LE.N)DO
W(J)=W(J)+A(I,J)
I=I+1
END WHILE
J=J+1
END WHILE
I=1
WHILE (I.LE.N)DO
J=1
V(I)=0
WHILE (J.LE.N)DO
V(I)=V(I)+A(I,J)
J=J+1
END WHILE
I=I+1
END WHILE
I=1
WHILE (I.LE.N)DO
SI(I)=Z(I)*V(I)
I=I+1
END WHILE
I=1
WHILE (I.LE.N)DO
J=1
S1=0
S2=0
L=1
WHILE (L.LE.NI(I))DO
S2=S2+IO(I,L)*I(I,L)+1)/(2.*V1)
L=L+1
END WHILE
S3=R1+1.+(K1-1.)/2.+S2
B1(I,J)=A(I,J)*Z(J)
S1=S1+S3*R(I,J)*(((S(I)*R(I,J))/B1(I,J))-1.)
J=J+1
END WHILE
D(I)=S1+R1+1
I=I+1
END WHILE
J=1
S=0
WHILE (J.LE.N)DO
S=S+W(J)*Z(J)
J=J+1

```

```
END WHILE
I=1
TD=0
WHILE (I.LE.N)DO
TD=TD+D(I)*SI(I)/S
I=I+1
END WHILE
PRINT,G1,S,TD
WRITE(9,1020G1,S
WRITE(10,103) S,TD
102 FORMAT(F8.4,F8.6)
103 FORMAT(F8.6,F10.5)
G1=G1+0.2
END WHILE
STOP
END
```

```
C SUBROUTINE QIJA(I,J,N,P,R,P1)
REAL P1,P(5),R(5,5)
INTEGER K
P1=1
K=1
WHILE (K.LE.N)DO
IF(K.EQ.I)GO TO 3
P1=P1*1.-P(K)*R(K,J)
3 K=K+1
END WHILE
RETURN
END
```

```
C SUBROUTINE QIJB(I,J,N,S1,P,R)
REAL S1,P(5),R(5,5)
INTEGER K,L
S1=0
L=1
WHILE (L.LE.N)DO
IF(L.EQ.I)GO TO 7
P2=1
K=1
WHILE (K.LE.N)DO
IF(K.EQ.L)GO TO 8
IF(K.EQ.I)GO TO 8
P2=P2*(1.-P(K)*R(K,J)
3 K=K+1
END WHILE
S1=S1+P(L)*R(L,J)*P2
7 L=L+1
END WHILE
RETURN
END
```

UBROUTINE QIJC(I,J,N,P,R,S2)

INTEGER K,L,M

REAL P(5),R(5,5)S22,S2,R3

S2=0

L=1

WHILE(L.LE.N)DO

IF(L.EQ.I)GO TO 9

S22=0

M=1

WHILE(M.LE.N)DO

IF(M.EQ.I)GO TO 10

IF(M.EQ.L)GO TO 10

P3=1

K=1

WHILE (K.LE.N)DO

IF(K.EQ.I)GO TO 11

IF(K.EQ.M)GO TO 11

IF(K.EQ.L)GO TO 11

P3=P3\*(1.-P(K)\*R(K,J))

11 K=k+1

END WHILE

S22=S22+P(M)\*R(M,J)\*P3

10 M=M+1

END WHILE

S2=S2+P(L)\*R(L,J)\*S22

9 L=L+1

END WHILE

S2=S2\*.5

RETURN

END

ENTRY

.3 .3 .4

.1 .6 .3

.6 .2 .2

PROGRAM TO FIND THE COEFFICIENTS IN THE THROUGHPUT EQUATION WITH  
N=3 AND M=2.

```
REAL A(9,9),B(9,9),Q0(9,9),Q1(9,9),Q2(9,9)
REAL G(5),R(5,5),P(5),V(5),W(5)
V1=7
READ, N
READ, (G(I),I=1,N)
DO 1 I=1,N
READ, (R(I,J),J=1,N)
1 CONTINUE
DO 2 I=1,N
P(I)=G(I)*EXP{-g(I)}
2 CONTINUE
I=1
WHILE (I.LE.N) DO
J=1
WHILE (J.LE.N) DO
CALL QIJA(I,J,N,P,R,Q0(I,J))
CALL QIJB(I,J,N,Q1(I,J),P,R)
CALL QIJC(I,J,N,P,R,Q2(I,J))
J=J+1
END WHILE
I=I+1
END WHILE
J=1
WHILE (J.LE.N) DO
I=1
WHILE (I.LE.N) DO
A(I,J)=(P(I)*R(I,J)/V1)*Q0(I,J)+.5*Q1(I,J)+.33*Q2(I,J)
B(I,J)=(P(I)*R(I,J)/V1)*Q0(I,J)+Q1(I,J)+.667*Q2(I,J)
PRINT, 'A(I,J) =', A(I,J)
I=I+1
END WHILE
J=J+1
END WHILE
J=1
WHILE (J.LE.N) DO
I=1
W(J)=0
V(J)=0
WHILE (I.LE.N) DO
W(J)=W(J)+A(I,J)
V(J)=V(J)+B(I,J)
I=I+1
END WHILE
PRINT, J, V(J), W(J)
J=J+1
END WHILE
STOP
END
```

```
SUBROUTINE QIJA(I,J,N,P,R,P1)
REAL P(1),P(5),R(5,5)
INTEGER K
P1=1
K=1
WHILE (K.LE.N)DO
IF(K.EQ.I)GO TO 3
P1=P1*(1.-P(K)*R(K,J))
3 K=K+1
END WHILE
RETURN
END
```

```
C SUBROUTINE QIJB(I,J,N,S1,P,R)
REAL S1,P(5),R(5,5)
INTEGER K,L
S1=0
L=1
WHILE (L.LE.N)DO
IF(L.EQ.I)GO TO 7
P2=1
K=1
WHILE (K.LE.N)DO
IF(K.EQ.L)GO TO 8
IF(K.EQ.I)GO TO 8
P2=P2*(1.-P(K)*R(K,J))
3 K=K+1
END WHILE
S1=S1+P(L)*R(L,J)*S2
7 L=L+1
END WHILE
RETURN
END
```

```
C SUBROUTINE QIJC(I,J,N,P,R,S2)
INTEGER K,L,M
REAL P(5),R(5,5),S22,S2,P3
S2=0
L=1
WHILE (L.LE.N)DO
IF(L.EQ.I)GO TO 9
S(22)=0
M=1
WHILE (M.LE.N)DO
IF(M.EQ.I)GO TO 10
IF(M.EQ.L)GO TO 10
P3=1
K=1
WHILE (K.LE.N)DO
IF(K.EQ.I)GO TO 11
IF(K.EQ.M)GO TO 11
IF(K.EQ.L)GO TO 11
P3=P3*(1.-P(K)*R(K,J))
```

```
11 K=K+1
    END WHILE
    S22=S22+P(M)*R(M,J)*P3
10 M=M+1
    END WHILE
    S2=S2+P(L)*R(L,J)*S22
9 L=L+1
    END WHILE
    S2=S2*.5
    RETURN
    END
```

## Chapter VI

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