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A Preliminary Design
of a TDMA System for FLEETSAT

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FOR THE COMMANDER

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

A PRELIMINARY DESIGN
OF A TDMA SYSTEM FOR FLEETSAT

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Group 67

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ABSTRACT

A typical UHF FLEETSAT channel is capable of supporting data rates in excess of 20 Kbps. Since the data rate of typical beyond line of sight Navy communications is 2.4 Kbps, the data from several users could be multiplexed on a single FLEETSAT channel. The time division multiplexing scheme described in this note would derive about 65 simultaneous 2.4-Kbps circuits from the nine 25-KHz channels for a representative mixture of ships, aircraft, submarines, and shore stations. The available circuits would be shared among a much larger pool of users by demand assignment. The system utilizes a central controller to allocate satellite resources, achieving rapid circuit assignments and pre-emptions with relatively high efficiency. Also described is a preliminary architecture for new equipment which would interface with existing Navy equipment and would perform demand assignment and time division multiplexing functions. The design of this new equipment relies upon digital processing and microprogrammable hardware, permitting straightforward upgrading for follow-on FLEETSAT systems.

CONTENTS

I.   INTRODUCTION AND SUMMARY

   A.   Introduction and Background

   The purpose of this note is to describe a demand assigned TDMA (time division multiple access) scheme which could be incorporated into the Navy FLTSATCOM system. In comparison with the initial plans for satellite usage, the proposed scheme represents a marked increase in both traffic throughput and operational flexibility. Moreover, the TDMA design and suggested implementation with microprogrammable hardware are such that relatively straightforward--hence, inexpensive--modifications would be required for adaptation to projected future communications systems. Finally, most system functions can be handled directly by the hardware and software, making the system almost as convenient to use as one with dedicated rather than demand assigned circuits.

   For maximum utility, the proposed TDMA system must incorporate terminals with a broad range of capabilities and requirements. Current user communications requirements are not precisely known, and indeed, future requirements may change as a result of introduction of satellite circuits. Also, traffic and channel conditions can be expected to fluctuate with time. To allow for these uncertainties, the system must be capable of operation over a broad and to some degree unknown range of conditions. Although the design described here satisfies these criteria, it is preliminary in that more analytical work and simulations are needed before it is completed. Emphasis in this note is given to the major system configurations and functions, and to the relationship between the operating environment and system functions. Subsequent to some more detailed design work, experimental hardware will be built to demonstrate the feasibility and capabilities of TDMA with FLEETSAT.

   The organization of this note is as follows: after some background information and a brief summary below, Section II describes the operating environment--the satellite and terminals, the RF channel, and the constraints and requirements of system users. Section III first discusses the implications of the operating environment on system design, then describes the functions of the system. Section IV discusses system realization.

FLEETSAT (officially FLTSAT) has nine 25-KHz UHF channels. With present plans, each channel will be used full time by a single net which has a typical data rate of 2.4 Kbps. Most terminals will be equipped with a transceiver, which includes a modem that can operate at up to 9.6 Kbps, and with a mini-computer for message buffering and interfacing the modem to various user I/O (input/output devices). Most FLEETSAT links themselves are actually capable of supporting data rates exceeding 20-Kbps. In principle, then, many 2.4-Kbps circuits could be multiplexed on each channel, significantly increasing the traffic throughput of the satellite. Because the satellite repeaters are hard limiting, time division is the appropriate method of multiplexing. (Other methods, such as frequency or code division, introduce power-control problems.)

A long-term goal in Naval telecommunications is to satisfy most BLOS (beyond line of sight) communications requirements by satellite circuits. Tactical BLOS requirements will probably exceed the capacity of FLEETSAT, and will thus require a new-generation satellite (some estimates of needed capacity are well over 100 simultaneous 2.4-Kbps circuits). Our present guess is that such a satellite--which we shall call FLEETSAT-II--would be launched in the mid-1980's.[*] Between the mid-1970's and the FLEETSAT-II era, then, the Navy will transfer only selected BLOS traffic from its present media to FLEETSAT-I. The scheme described in this note could typically provide about 65, 2.4-Kbps FLEETSAT-I circuits for a mixture of ships, submarines and aircraft. The TDMA modem needed for this scheme would be based upon microprogrammable hardware, and because of procurement procedures, probably would not be available for widespread fleet usage until the late 1970's. The growth of satellite communications capability might, therefore, be as follows: During the initial phase of FLEETSAT-I, growing numbers of terminals will be equipped for satellite communications with

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[*] At present, FLEETSAT-II does not refer to a specific satellite or program. The notation is used herein to designate the Navy satellite system of the 1980's which might actually be a portion of a shared tactical satellite system. To avoid possible confusion, the initial satellite will be designated FLEETSAT-I in this report.

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presently available modems. In this interim period, some 25, 2.4-Kbps circuits could be obtained by making software (and minor hardware) changes in present equipment. Beginning in the late 70's, terminals would be equipped with the more advanced TDMA modems, and the number of circuits derived from FLEETSAT-I would grow from 25 to about 65. With the launch of FLEETSAT-II, the TDMA modem would be reconfigured, merely by changing the programs in microprocessors to be compatible with the FLEETSAT-II multiple access format. The new TDMA modem, coupled with some related interim changes to present equipment would then allow an orderly transfer of tactical BLOS communications to satellite circuits and would, with the same hardware, provide spectrum spreading for anti-jam protection. One of two approaches can be taken in order to assure this growth compatibility:

Either (1) some preliminary design work can first be carried out on the schemes to be incorporated into the follow-on system, with compromises in the resulting communications concepts to adapt them to FLEETSAT-I;

or (2) the initial phases of the FLEETSAT-I communications schemes can be more or less optimized with only superficial regard to any follow-on system, and then upgraded to perform with those systems.

Although the first approach may involve more effort in the short term, it is preferred because in the long run it will result in a system with superior performance and capabilities, and in the short term it will yield comparable capability.

B.   Summary and Conclusions

The demand assigned TDMA system described in this note consists of the FLEETSAT-I satellite and the shore, ship, aircraft and submarine terminals in the satellite coverage area. Each terminal would have, in addition to such existing equipment as transceivers, new equipment to perform all the functions necessary to achieve both demand assignment and time division multiple access. This new equipment is called a terminal access controller and modem (TACM). Efficient TDMA operation also requires minor changes to existing equipment.

A shore terminal serves as the system controller, generating timing for TDMA and assigning circuits on request to mobile terminals. Ships designated as standby controllers would assume these functions in the event of failure of the shore station. Framing pulses, which provide basic system timing, are on one 25-KHz channel for ships and on another 25-KHz channel for aircraft and submarines (which have lesser communications capabilities than ships). The framing pulses on these two channels divide all nine FLEETSAT-I channels into 1-second frames. To gain initial access to the system, a terminal first synchronizes to the framing pulses in the appropriate channel. Having thereby achieved receive timing, the terminal obtains transmit timing by using a ranging signal and compensating its clock for the distance to the satellite. The terminal may then request a circuit, i.e., a time slot in one of the nine channels. The duration of the slot is based upon the user I/O data rate and upon the link capabilities, and the location of the slot is based upon the type of terminal and upon the existing traffic to the terminal. If a suitable circuit is available, the controller assigns it. If not, but if the precedence of the request is high, the controller preempts an existing circuit or circuits. To assure rapid ($\sim$3 second) assignment and preemption, each terminal is required to monitor a control slot in each frame. About 25% of each of the two control channels (less than 6% of the total satellite capacity) is used for control and signaling information.

The proposed TDMA scheme can realize high utilization of the satellite capabilities, allowing up to 109, 2.4-Kbps circuits over the nine FLEETSAT-I channels. The actual number of circuits will generally be considerably less than the maximum of 109, depending, for example, on the number of submarines and aircraft that are communicating. The use of demand assignment with TDMA permits the transfer to FLEETSAT-I of a total number of BLOS nets much greater than the actual number of circuits that can be handled by the satellite at any one time.

In addition to efficiency of utilization, significant operational flexibility is achieved by the system design. The central controller allocates

satellite resources according to link and terminal capacities, traffic load, channel conditions, and traffic precedence. As one important example of the system flexibility, the frame structure and assignment algorithms permit a half duplex terminal to participate in two or more nets simultaneously.

Simplicity of system usage is enhanced by the large degree to which circuit request procedures would be automated in the TACM and in the central controller. Since each request for a circuit would contain a terminal address as well as a net address, messages can be transmitted from terminal to terminal without participation by other net members. This scheme also permits multiple simultaneous circuits to be established within a single net. Nets can, of course, operate with all net members copying a message.

As noted in the Introduction, the TACM will be realized largely with microprogrammable hardware, thereby simplifying any upgrading needed for operation with follow-on satellite systems. The central controller would be implemented primarily in software on a small general-purpose computer. The functions that must be performed by the TACM and those that must be carried out by the controller may appear complicated in a verbal description, but their development and implementation would be relatively straightforward and are certainly within the capability of present-day equipment. The pre-programmed and automated procedures for handling circuit requests and other system functions facilitate utilization of the system and make its operation appear almost transparent to the user.

II. OPERATING ENVIRONMENT

This section discusses those characteristics which influence the size and structure of the TDM frame and of the communication slots, control slots, and guard times within the frame. Information for this section was derived from numerous documents, both formal and informal, which describe FLEETSAT and naval telecommunications, from visits to a COMMSTA[*], from conversations with Navy communication personnel, and from on-going studies of FLEETSAT evolution being conducted at Lincoln Laboratory.

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[*] Short for NAVCOMMSTA (Naval Communications Station).

A.   FLEETSAT

The synchronous satellite containing FLEETSAT has an Air Force portion which is part of AFSATCOM, and a Navy portion, which we call FLEETSAT-I in this note.   The UHF communications portion of FLEETSAT-I has nine 25-KHz bandwidth channels which are candidates for demand assigned TDMA.   Two of these nine channels have somewhat higher EIRP than the other seven.   The actual satellite EIRP can be specified in a number of ways and indeed may change with the relative location of the receiving terminal and with the age of the satellite. For definiteness in this report, we shall assume that the higher power channels have an EIRP of 28 dBW and the remaining seven have 26 dBW; these are representative, although conservative values.

FLEETSAT-I also has a Fleet Broadcast channel which normally has an SHF uplink and a 25-KHz UHF downlink (separate from the other nine UHF channels).   One of the weaker (26 dBW) TDMA channels is a standby channel for Fleet Broadcast in event of a failure of the normal mode.

The uplinks span a 25-MHz band centered at about 300 MHz; the downlinks span a similar band centered at about 260 MHz.   Each 25-KHz channel has a hard limiting repeater which translates the frequency approximately 40 MHz.   The 1-dB bandwidth of each channel filter is 24 ± 0.5 KHz, and the center frequency of the filter is within 1 kHz of its nominal value. The frequency standard in the satellite has an accuracy of one part in 10^7 to end of life.

The structure of FLEETSAT-I replenishment satellites is still under study.   However, although a replacement satellite may be somewhat modified, its communication capability for TDMA will probably not differ appreciably from that of the original.   FLEETSAT-II, on the other hand, may well be substantially different from FLEETSAT-I.   The uplink may be frequency division multiplexed with frequency hopping for minimizing effects of electromagnetic interference.   The satellite itself may perform such processing as de-hopping, demodulation, and circuit assignment.   The downlink would probably be TDM, but in one wideband channel rather than a number of narrowband channels as in FLEETSAT-I[*].

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[*]   LES-10, an experimental satellite presently in the conceptual phase at Lincoln Laboratory, could, if deployed, demonstrate many of these features of an advanced satellite system.

TABLE 2-1

CHARACTERISTICS OF FLEETSAT TERMINALS

	Typical Number Per Coverage Area	Antenna Gain (dB)	Method Of Separating Transmit & Receive Paths	Transceiver Type	NUMBER OF TRANSCEIVERS		TURN AROUND TIME (msec)		FREQUENCY SETTLING TIME (msec)	
					Full Duplex	Half Duplex	Present	Possible with Mods	Present	Possible with Mods
COMMSTA	2	18	Diplexer	WSC-5	2	6	125	25	20-50	NA
				WSC-3	0	1-9	40	0.5	3	1
SHIP	150	12	Diplexer	WSC-5	1	3	125	25	20-50	*
				WSC-3	0	1-4	40	0.5	3	1
SUBMARINE	40	-3	Switch	WSC-3	0	1	40	40	3	1
AIRCRAFT	10	0	Switch	ARC-143	0	1	0.5	*	20	20
				ARC-156	0	1	1	*	20-165	10-80

* Requires extensive modifications.

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B.   FLEETSAT Terminals

1.   Equipment

FLEETSAT terminals vary considerably in structure and capability.   In
this section we discuss the characteristics of the various user terminals
which are most important in a demand assigned TDMA system.   Such characteristics,
summarized in Table 2-1, include the number of each terminal type in the
coverage area and the number and type of transceivers within each terminal.
The most important factors in transceiver performance are turnaround time,
frequency settling time, and whether the transceiver is full or half duplex.[*]

The coverage area of each FLEETSAT-I satellite will include one or
two COMMSTAs.   The total number of FLEETSAT-I ship terminals equipped with a
transmit capability is assumed here to be 450.   Although four satellites will
be orbiting simultaneously to provide worldwide coverage, we shall assume
that 150 terminals are in the coverage area of one satellite.   By a similar
argument, the number of submarines in a satellite coverage area is assumed to
be 40, and of FLEETSAT-I aircraft terminals is assumed to be 80; however,
only 10 of these aircraft are likely to be airborne simultaneously.

Ships use OE-82B antennas, which have 12 dB gain.   COMMSTAs use the
equivalent of four OE-82B's for 18 dB gain.   The OE-82B includes a diplexer
to separate the transmit and receive path, so the path from transceiver to
antenna on a ship or COMMSTA is full duplex.   Submarines and aircraft,
however, use omnidirectional antennas (about 0 dB gain for aircraft and -3 dB
for submarines) and separate the transmit and receive paths with a switch.
The switch in an aircraft installation is solid state, with reaction time in
the microsecond range, while the switch on a submarine installation is
electromechanical, with reaction time about 40 milliseconds.

As of this writing, COMMSTAs and ships can have WSC-5 or WSC-3
transceivers.   However, shipboard WSC-5's are to be replaced by WSC-3's, so
that in the future, apparently only COMMSTAs will have WSC-5's.   A single
WSC-5 has 1 full duplex and 3 half duplex transceivers.   COMMSTAs have dual
WSC-5's.   WSC-5's have R-T (receive-to-transmit) turnaround times of

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[*] Much of the data on these parameters was derived from information provided
by Computer Sciences Corporation.

125 msec, which can be reduced to 25 msec with equipment modifications. (Equipment modifications considered feasible are those that do not require major alterations.) The T-R turnaround time of the WSC-5 is less than 25 msec (or can be made so). The frequency settling time following a frequency change is between 20 and 40 msec, depending on the magnitude of the change. Reduction of this time has not been considered because it would apparently require extensive equipment changes.

The R-T and T-R turnaround times of the WSC-3 are presently 40 msec each, a time that was designed to be consistent with the switching time of the T/R switch in a submarine installation. These turnaround times could be reduced to ∼0.5 msec with circuit changes. The frequency settling times of the WSC-3 is presently 3 msec; however, modifications already planned for LES-8/9 compatibility will reduce it to 1 msec.

Because of the electromechanical T/R switch in a submarine installation, the turnaround time for its WSC-3 is 40 msec. Replacing the electromechanical switch with a solid state device would reduce the time to the 1 msec possible for a ship, as well as improve the long term reliability of the switch.

Aircraft have single transceivers, which can be either the ARC-143 or the ARC-156. Both sets have rapid turnaround times: 0.5 msec for the ARC-143 and 1 msec for the ARC-156. However, both sets have fairly long frequency settling times. The ARC-156 has 20-165 msec, depending on the magnitude of the change. This can be reduced to 10-80 msec with some circuit changes. The ARC-143 has 20 msec, which apparently cannot easily be reduced. In addition, switching the ARC-143 from one UHF channel to another requires one second. This could be reduced to 15 msec by adding a control box and making some circuit changes.

The system design presented in the following sections will generally assume that the equipment modifications mentioned above will be performed, and therefore the improved values are used for turnaround and settling times. More specific suggestions on equipment alterations will be given in Sec. IV.

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2. Time and Frequency Errors

The data pertinent to frequency and timing errors at mobile terminals are summarized in Table 2-2. The reference for motion is the satellite and for time is a standard having accuracy better than one part in 10^8. The long-term stability of the frequency standards in both the WSC-3 and the WSC-5 is one part in 10^7 per month. After one year, therefore, the standard might have drifted by one part in 10^6; this is the value that was used in computing the frequency offsets and the clock drift. Also included is an additional 30 Hz of offset which may be introduced by errors in the satellite's standard. Assumed velocities for Doppler calculations are 35 kt for ships and 700 kt for aircraft. In addition, motion of the ship's antenna (due to pitching) could add $\sim$10 Hz to the Doppler, and satellite motion could add an additional $\sim$10 Hz. The Doppler rates are based upon 2g acceleration of the ship's antenna (caused by heave, roll) and a like value for aircraft acceleration. Range drift values include $\sim$2 μsec/min from satellite motion.

TABLE: 2-2

FREQUENCY OFFSETS AND DRIFT RATES FOR MOBILE TERMINALS

	Freq. Offset + Doppler Shift ($\pm$ Hz)	Doppler Rate ($\pm$ Hz/sec)	Clock Drift ($\pm \mu$ sec/min)	Range Drift ($\pm$ sec/min)
Ship	330 + 40	20	60	6
Aircraft	330 + 370	20	60	75

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C.   User Requirements and Constraints

Terminals are organized into communication nets. Each net would have
a unique crypto key, and hence all communications, whether from one terminal
to another or from one terminal to a group of terminals, must be within a
net. Each communication possesses a specified precedence and constitutes a
message. In addition to precedence, important characteristics of a message
include the nature of the message (store-and-forward or interactive; terminal
to terminal, or terminal to many terminals) and I/O data rate. Data rates
are in general 75×2^n (n > 0) bps and 8000m (m > 1) bps. An appropriate
range of FLEETSAT user data rates is 75 bps (teletype) to 32 Kbps (high
quality secure voice).

1.   System Responsiveness

There are three major aspects of system responsiveness. The first,
initial acquisition time, is the time between bringing a FLEETSAT terminal
to an operate condition and being able to communicate with the terminal. This
could also be termed as the time for an inactive terminal to become active.
A design goal for this quantity under nominal traffic conditions is 10 seconds
or less, but during heavy traffic, it can be expected to increase somewhat.
The probability of false acquisition, i.e., of a terminal mistakenly thinking
that it is synchronized and can transmit, must be very low, say less than
10^{-6}, because of the harmful effect such a terminal could have on the overall
system. If, for example, this probability is 10^{-6}, then if there are 200
acquisitions per day (once for each terminal), the probability of a false
acquisition within a one year period is less than 0.1.

The second aspect is the system response time, defined as the time
between an active terminal making a request for service and receiving a
reply to that request. (The reply may, in fact, be that "service cannot be
provided now.") An important design goal is that a user should see a more
or less uniform response time even under varying conditions. On the other
hand, the actual response to a request might very well vary with the traffic
structure. Under stressed conditions, for example, more of the traffic
might have high precedence and therefore require very rapid access to communi-

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cations links, while all low precedence requests might automatically evoke the system response that "all circuits are busy". The system should be able to provide a response time on the order of three seconds with high confidence.

The final aspect of responsiveness is the preemption capability. There are two basic kinds of preemption: (1) if all satellite circuits are assigned, a high precedence call can preempt a circuit being used by a lower precedence call (preemption of satellite capacity), (2) if a particular terminal is operating at capacity, a high precedence incoming or outgoing call can preempt a lower precedence ongoing call (preemption of terminal capacity). A reliable and rapid preemption capability is an important attribute of a military communications system with limited resources. Indeed, the success of demand assignment schemes may depend upon the ability to promptly provide a high precedence user with what appears to be a dedicated circuit. The requirement for preemption time is therefore taken to be 10 seconds.

Another aspect of responsiveness is the talker-to-listener turnaround time for voice traffic. Subjective tests by the Bell System [1] have shown that turnaround times of 600 msec or less are not objectionable, so this value is a desirable goal. However, tests conducted for military applications with users familiar with push-to-talk equipment indicate that delays of 1-2 seconds are not unduly objectionable. Since the minimum turnaround time is roughly equal to the frame duration, these values dictate a frame duration no longer than ~ 1 sec.

2. Traffic

The two types of traffic that will use FLEETSAT are data and voice.
Data traffic is either store-and-forward or interactive. Interactive data
requires fairly short turnaround times, although not as short as the values
given above for voice: several seconds should be adequate. Store-and-forward
data will generally be buffered prior to transmission in order to increase the
length of a transmission block and thereby increase system efficiency.
Delivery times ranging from several minutes to several hours (depending upon
precedence) can be tolerated. Also, store-and-forward traffic often requires
message acknowledgments, but they are considered to be outside the TDMA
system; that is, the recipient rather than the system must initiate the
acknowledgment.

Statistics on request rate and call duration for nets and terminals
are not specifically known. For the purpose of sizing FLEETSAT-II, some
preliminary traffic studies were made which suggested an average request
rate of ∿1.4 calls per second*. This figure is based upon some rough estimates
provided by Navy personnel, but it is consistent with several present-day
predictions of future Navy satellite traffic requirements. The 1.4 call per
second average rate is probably somewhat conservative (i.e., it represents
an overdesign) because it assumed that all calls in a 24-hour period occur
within eight hours, and because many of the calls included in the total will
actually be borne by Fleet Broadcast during the FLEETSAT-I era. Despite the
above uncertainties, and in order to provide some definiteness during the
design, the nominal traffic statistics are taken to be the following:

Initial acquisitions: times between terminals performing initial
acquisition are exponentially distributed with a mean of
10 sec.

New requests for service: Poisson distributed with a mean of 1.4
requests/sec.

Duration of calls: exponentially distributed with mean values of
300 sec for voice, 12 Kbits for data, (e.g., 5 sec at 2.4 Kbps).

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* The requests in a coverage area were presumed to correspond to 10 large
ships having 2500 messages per day, 50 medium ships having 250 messages per day,
plus 100 small ships having 25 messages per day.

Clearly, the traffic patterns will vary markedly with time, with perhaps double the acquisition and request rates under heavy traffic conditions. It is essential that the overall design be relatively insensitive to changes from the above defined nominal conditions.

3. Traffic Reliability

The required bit error rates P_e for the different types of traffic are:

$P_e < 10^{-2}$ for 16–32 Kbps voice;

$< 10^{-3}$ for 2.4 Kbps voice;

$< 10^{-5}$ for data.

The requirements on data output must be maintained regardless of channel or equipment conditions. If conditions are such that the error performance cannot be met, then data output should be suppressed. In other words, a specific requirement could be established on the failure to receive transmitted data. The requirement would be stringent under nominal conditions, but would be relaxed under degraded conditions.

4. Security

In addition to requirements relating to traffic conditions and responsiveness, there are requirements for system security. All traffic must be encrypted. This pertains not only to communication traffic, but also to signaling. In addition, traffic analysis should be deterred where possible. Hence, idle circuits should contain dummy data so that to an outside observer, the system always appears to be fully utilized.

TABLE 2-3

UPLINK CALCULATIONS FOR FLEETSAT

	COMMSTA STAGES IN MULTICOUPLER			SHIP STAGES IN MULTICOUPLER			SUB	AIRCRAFT
	2	3	4	0	1	2		
P_A (dBW)	20	20	20	20	20	20	20	20
-Multicoupler Loss (dB)	6.8	9.8	12.8	0	3.8	6.8	0	0
-Line Loss (dB)	3	3	3	4	4	4	2	2
+Antenna Gain (dB)	18	18	18	12	12	12	-3	0
EIRP (dBW)	28.2	25.2	22.2	28	24.2	21.2	15	18
-Path Loss (dB)	174.5	174.5	174.5	174.5	174.5	174.5	174.5	174.5
+Sat. Antenna Gain (dB)	10	10	10	10	10	10	10	10
$-N_o$(1000°K) dBW/Hz	-199	-199	-199	-199	-199	-199	-199	-199
$(P_r/N_o)_{Up}$ (dB Hz)	62.7	59.7	56.7	62.5	58.7	55.7	49.5	52.5

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D.   Terminal-to-Terminal Burst Rates

The 75-bps to 32-Kbps range of data rates mentioned earlier are the input/output rates that a FLEETSAT terminal user would see. With TDMA, the data is transmitted at a burst rate which may be much higher than the actual data rate. In this section we investigate the burst rate that a particular user-to-user link will support. The ratio of burst rate to data rate is a direct measure of the improvement in throughput possible with time division multiplexing. For many FLEETSAT-I links, this ratio can be as high as 13.

Uplink calculations are summarized in Table 2-3. The received signal power and noise spectral density (assumed Gaussian) are denoted by P_r and N_o, respectively. All transmitters are assumed to have 100-watt output power. Multiple transceiver installations have losses of 0.8 dB plus 3 dB for each multicoupler stage. Line losses vary from 2 dB on submarines to 4 dB on ships. Terminal antenna gains vary from -3 dB for a submarine to 18 dB for a COMMSTA. The table shows that because of multicoupler losses, the difference in EIRP between a fully equipped COMMSTA (9 transceivers) and the weakest terminal (a submarine) is only ∿7 dB. In contrast with this, a ship with a single transceiver has EIRP of 28 dBW, fully 13 dB more than a submarine. Hopefully, alternatives or improvements to the present multicouplers can be found in order to reduce the present losses.

As of this writing, a modification to FLEETSAT-I is in progress which will reduce the receiver antenna gain to approximately 10 dB (from 13.3 dB). Although the 10 dB figure may be optimistic, it has been used here for the uplink calculations since the 1000°K receiver noise temperature may in fact be pessimistic. The resulting P_r/N_o of the uplinks, not including any margin, ranges from 49.5 dB to 62.7 dB, although for fully equipped terminals the upper limit of the range is 6 dB lower.

TABLE 2-4

DOWNLINK CALCULATIONS FOR FLEETSAT

	COMMSTA		SHIP		SUB		AIRCRAFT	
EIRP (dBW)	28	26	28	26	28	26	28	26
-Path Loss (dB)	173	173	173	173	173	173	173	173
+Antenna Gain (dB)	18	18	12	12	-3	-3	0	0
$-N_o(1000°K)$(dBW/Hz)	-199	-199	-199	-199	-199	-199	-199	-199
$(P_r/N_o)_{down}$ (dB Hz)	72	70	66	64	51	49	54	52

The downlink P_r/N_o range is considerably wider than the uplink range, as indicated by the calculations summarized in Table 2-4 for the assumed 26-dBW and 28-dBW EIRPs. The downlink P_r/N_o, excluding margin, ranges from 49 dB for a submarine on a weaker channel to 72 dB for a COMMSTA on a stronger channel, yielding a total range of 23 dB. (Note that multicoupler losses do not affect the received signal.)

Most of the parameters in the uplink and downlink P_r/N_o calculations are subject to variations, and hence margin must be allowed for each link. Ideally, a link margin should be based on the statistics of performance of each portion of the link and upon implementation degradation. Since such statistics are to a large degree unknown at present, a 6-dB margin will be assumed for each uplink and downlink. This margin is meant to allow for degradations that are expected to occur under more or less typical operating conditions, e.g., moderate antenna motion on a ship. The following section describes some of these degradations. In some situations, however, more severe disturbances can occur, e.g., the effective loss of a significant fraction of signal strength because of a very high sea state. In such a situation the margin allocated might not be sufficient, and the system must therefore make other provisions. In any event, the system should possess the capability of enabling communication with a terminal suffering larger than normal degradations.

The performance of the hard limiter in each satellite repeater may be specified by the ratio of the output to input signal-to-noise ratios:

$$\gamma = \frac{SNR_{out}}{SNR_{in}}$$

Since the channel is nonlinear, γ varies as a function of the input SNR. The quantity SNR_{in} is equal to $(P_r/N_o W)_{up}$, where W is the bandwidth, and the total satellite output power is constant, equal to $(P_r)_{down}$. The subscripts "up" and "down" refer the quantity to the satellite receiver and the earth terminal receiver, respectively. The satellite output power devoted to signal is therefore

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$$\frac{\gamma(P_r)_{up}}{\gamma(P_r)_{up} + (N_oW)_{up}} \cdot (P_r)_{down}$$

and devoted to noise is

$$\frac{(N_oW)_{up}}{(\gamma P_r)_{up} + (N_oW)_{up}} \cdot (P_r)_{down} \qquad .$$

At the earth terminal, then, the effective received SNR is

$$\left(\frac{P_r}{N_oW}\right)_{eff} = \frac{\dfrac{\gamma(P_r)_{up}(P_r)_{down}}{\gamma(P_r)_{up} + (N_oW)_{up}}}{\dfrac{(N_oW)_{up}(P_r)_{down}}{\gamma(P_r)_{up} + (N_oW)_{up}} + (N_oW)_{down}}$$

If $W_{up} = W_{down}$, this becomes

$$\left(\frac{P_r}{N_o}\right)_{eff} = \frac{\gamma\left(\dfrac{P_r}{N_o}\right)_{up}\left(\dfrac{P_r}{N_o}\right)_{down}}{W\left[\left(\dfrac{P_r}{N_oW}\right)_{down} + \gamma\left(\dfrac{P_r}{N_oW}\right)_{up} + 1\right]} \qquad .$$

Finally, it can be demonstrated that for all cases of interest, the approximation $\gamma = 1$ yields results within a fraction of a dB of the actual value of effective P_r/N_o.[*] Thus,

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[*] Cases of interest involve a signal in Gaussian noise interference, for which γ varies from $\pi/4$ for low $(P_r/N_oW)_{up}$ to 4 for high $(P_r/N_oW)_{up}$. The approximation for $(P_r/N_o)_{eff}$ is accurate to within ~ 0.5 dB.

$$\left(\frac{P_r}{N_o}\right)_{eff} \approx \frac{\left(\frac{P_r}{N_o}\right)_{up}\left(\frac{P_r}{N_o}\right)_{down}}{W\left[\left(\frac{P_r}{N_o W}\right)_{up} + \left(\frac{P_r}{N_o W}\right)_{down} + 1\right]} \quad .$$

Table 2-5 presents the effective P_r/N_o for all possible links composed of uplinks from Table 2-3 and downlinks from Table 2-4, <u>after subtracting 6 dB margin on both the uplink and the downlink</u>. The table has two entries for each link: $(P_r/N_o)_{eff}$, and link burst rate for $E_b/N_o = 6$ dB (typical for well-coded communications having efficient modulation structure). The P_r/N_o's of the uplinks and downlinks are also shown (with margins) so that one can readily determine whether a link is uplink limited or downlink limited; thus, a transmission is uplink limited, for example, if $(P_r/N_o)_{up}$ < $(P_r/N_o)_{down}$, and the burst rate can be increased only by an improvement in the uplink parameters, such as power of the transmitting terminal or gain of the satellite receiving antenna. Asterisks indicate those calculated burst rates that would exceed 32 Kbps, which is probably a practical limit due to the 25-KHz channel bandwidth limitation. Note that this limit is not achievable on links from fully equipped COMMSTAs or ships, although the COMMSTA, at 28 Kbps, comes close. Note also that transmissions to submarines, even on a 28-dBW channel, is limited to 7 Kbps or less, even with the most effective uplink and with efficient coding. Transmission from submarines is even more restricted, ∿5.5 Kbps at best. With time division multiplexing, however, even this rate would leave more than half a channel for other users (e.g., up to seven ships). Fortunately, however, the large majority of FLEETSAT communications will be among large ships and COMMSTAs, having

TERMINAL-TO-TERMINAL DATA RATES FOR FLEETSAT-I

FROM	Pr/No DOWN	Pr/No UP	COMMSTA 72 <28>	COMMSTA 70 <26>	SHIP 66 <28>	SHIP 64 <26>	SUB 51 <28>	SUB 49 <26>	AIRCRAFT 54 <28>	AIRCRAFT 52 <26>
COMMSTA	62.7	(2)	56.2 / *	55.9 / *	55.0 / *	54.2 / *	44.5 / 7.1	42.6 / 4.6	47.3 / 13.3	45.4 / 8.8
COMMSTA	59.7	(3)	53.4 / *	53.3 / *	52.7 / *	52.2 / *	44.1 / 6.4	42.2 / 4.2	46.6 / 11.5	44.9 / 7.8
COMMSTA	56.7	(4)	50.5 / 28.5	50.5 / 27.9	50.1 / 25.8	49.8 / 24.1	43.3 / 5.4	41.6 / 3.6	45.6 / 9.1	44.1 / 6.4
SHIP	62.5	(0)	56.0 / *	55.8 / *	54.8 / *	54.1 / *	44.5 / 7.0	42.6 / 4.6	47.2 / 13.2	45.4 / 8.7
SHIP	58.7	(1)	52.5 / *	52.3 / *	51.9 / *	51.4 / *	43.8 / 6.1	42.1 / 4.0	46.3 / 10.8	44.7 / 7.4
SHIP	55.7	(2)	49.6 / 22.8	49.5 / 22.4	49.2 / 21.0	49.0 / 19.7	42.9 / 4.9	41.3 / 3.4	45.1 / 8.2	43.7 / 5.9
SUB	49.5	(0)	43.4 / 5.6	43.4 / 5.5	43.3 / 5.4	43.2 / 5.2	39.5 / 2.3	38.2 / 1.7	41.1 / 3.2	40.1 / 2.6
A/C	52.5	(0)	46.4 / 11.0	46.4 / 10.9	46.2 / 10.5	46.0 / 10.1	41.4 / 3.5	40.0 / 2.5	43.3 / 5.3	42.1 / 4.1

(In each data cell: $(P_r/N_o)_{eff}$ (dB) / Data Rate (Kbps))

( ) Number of multicoupler stages;   < > Assumed downlink EIRP, dBW;   * Bandlimited to 32 Kbps

Numbers include 6 dB margin on uplink and downlink; Data rates based upon E_b/N_o = 6 dB (10^{-5} bit error rate)

TABLE 2-5
TERMINAL-TO-TERMINAL DATA RATES FOR FLEETSAT-I

allowable burst rates on the order of 20 Kbps, a value which permits
time division multiplexing of eight 2.4 Kbps circuits on one 25-KHz
channel. A terminal configuration with 3 or 6 dB less loss than the
present multicoupler would permit fully equipped COMMSTAs and ships
to operate at the band limited burst rate, conceivably allowing up to
thirteen 2.4-Kbps circuits to be multiplexed on one channel.

E. Deviations from Ideal Operating Conditions

This section describes some important deviations from the idealized
hard-limiting channel with Gaussian noise. The intent is to provide a semi-
quantitative indication of the disturbances that may be encountered; careful
analysis and experimentation are required in each area in order to obtain
detailed information on the actual communications degradations that would
take place and on methods to reduce the effect of the disturbances.

1. Antenna Motion[*]

The planned OE-82 shipboard antenna installations will be stabilized
only with respect to bearing, and therefore ship's motion will result in a
partial loss of signal energy if the satellite is temporarily not in the
central portion of the main antenna beam. The beamwidth of the OE-82
antenna at the 2 dB points is approximately 30°. Accordingly, pitch and yaw
will generally not cause appreciable degradation, except perhaps for small
ships in extreme sea states. Roll, however, can produce more serious
degradations: For example, in sea state 7, the roll amplitude of a large
ship is on the order of $\pm30°$, and for a medium-sized ship it is $\pm40°$. In
the worst case, the latter amplitude can cause a peak gain reduction of 13 dB,
with a loss greater than 6 dB about half the time. Of course, the severity
of the degradation is a function of both the satellite elevation angle and
the ship's heading.

It is interesting to note that the period of a ship roll is on the
order of 10 seconds, and therefore the time and amplitude characteristics of

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[*] Many of the values cited in this section were derived from data provided
by the Naval Research Laboratory.

the gain are not unlike those introduced by ionospheric scintillation (see Sec. E-3 below). Techniques designed to combat the effects of scintillation may thus also prove useful in minimizing the problems introduced by antenna motion.

2. RFI

Shipboard (or aircraft) RFI (Radio Frequency Interference) is generated by radar pulses of such magnitude that even if the radar antenna is not aimed in the direct beam of the satellite receiving antenna, the received energy is sufficient to swamp out the satellite signal. A blanking signal from the radar that would provide the receiver with information on the timing of the pulses is not presumed to be available, although such a signal, internally generated by the receiver, might be of value in reducing the effect of the RFI. (An externally generated blanking signal would not be sufficient protection against all RFI because the interference could be generated at some other nearby location.)

Order-of-magnitude values for the pertinent pulse RFI parameters for shipboard radar are up to 200-μsec-wide pulses occurring at a repetition rate of up to 250 pulses/sec. The effect of RFI can be expected to be most damaging on short bursts of data. With the above values, for example, RFI would affect about 5% of the received signal, but could affect about 10% of the bits in a data burst (viz. if the RFI pulses overlap bit boundaries or if they occur at both the beginning and the end of a short burst).

In addition to pulse RFI, large CW signals (e.g., from line-of-sight users) could also generate interference. To reduce possible degradation, appropriate filtering must be included in the receiver to eliminate the effect of these unwanted signals.

3. Scintillation

The amplitude and phase fluctuations experienced by signals that pass through the ionosphere are called scintillation [2]. The fluctuations are frequent enough and can be severe enough that precautions must be taken to protect UHF satellite communications links from their effect.

Scintillation is predominantly a nighttime phenomenon, occurring mainly in polar regions and in a band approximately 30° wide about the geomagnetic equator. (In the northern hemisphere, the polar region extends north of the 50° geomagnetic latitude.) Scintillation fades can be as deep as 10-15 dB with durations on the order of seconds; the time between deep fades is also a statistical parameter but has an order of magnitude of 10 seconds. In the worst case, a link experiencing scintillation behaves as a Rayleigh fading channel for which the probability distribution of the ratio of the actual received signal power to the nominal, i.e., average-signal power is given by [3]

$$P[(P_r/\overline{P}_r) > \alpha] = e^{-\alpha}$$

The durations of fades below $\overline{P}_r$ are distributed roughly exponentially, with mean fade duration $\overline{t}_{fade} \approx 4(P_r/\overline{P}_r)^{0.6}$ seconds. For example, when this worst case scintillation is present, the received SNR exceeds the nominal value only 37% of the time; with 3 dB link margin, the received SNR exceeds the required value 61% of the time, and fades below nominal last about 2.6 sec on the average. These figures indicate that because of the fading statistics, margin alone is not a practical means of combatting scintillation. Rather, a combination of margin, coding, and repeated transmissions must be used to maximize throughput during scintillation.

4. Multipath

Because of the poor directivity of aircraft antennas, satellite signals reflected from the earth's surface can interfere with the direct satellite signal to produce interference. Experimental observations have shown that fading due to multipath is produced primarily by the specular component of the reflected energy. Specular reflection is of the same type as that from a smooth surface; in particular, it is directional and coherent, with fairly steady amplitude.

The additional distance traveled by a multipath signal is greatest for an aircraft directly beneath the satellite, and in that case is equal to twice

the aircraft altitude. For such an aircraft at 10 Kft, for example, the relative delay of the multipath signal is approximately 20 μsec. Three observations can now be made regarding the effect of multipath of a FLEETSAT-I communications system: (1) the aircraft that will use the system generally fly at relatively low altitudes; (2) bandwidth limitations require that the symbol duration be greater than about 50 μsec; and (3) for an aircraft experiencing maximum or near maximum multipath delays, even the limited directivity of its antenna provides some multipath protection. The conclusion, then, is that for FLEETSAT-I, the multipath delay is much less than the duration of a symbol, so that multipath, if present, will not cause much intersymbol interference, but rather can be expected to affect only the received energy on a symbol-by-symbol basis. With this conclusion, it is clear that coding alone (unless perhaps the data is interleaved) cannot provide multipath protection for FLEETSAT-I, although frequency, time, or antenna-diversity techniques can be used to advantage.

The directivity of the OE-82 antenna can be expected to eliminate or certainly to diminish multipath problems for ships. However, at low elevation angles, and especially when there is significant ship roll, the presence of mltipath can introduce some degradation. For example, with unity reflection coefficient (worst case) and a 15° elevation angle, an OE-82 aimed at a synchronous satellite will receive a multipath signal approximately 6 dB below the direct signal. Clearly, any roll will result in additional degradation because there will be times when the direct signal experiences the reduced antenna gain while the multipath signal experiences increased gain. On a submarine, the multipath problem may be even more severe because its antenna is omnidirectional and because it can also experience large roll amplitudes. With both submarines and ships, however, the multipath signal is received within a fraction of a microsecond of the direct signal, and therefore only diversity techniques can be used to counter its effect.

III.   SYSTEM OPERATION

The information presented in Sec. II provides some insight into the variety of requirements and constraints that are placed upon a FLEETSAT TDMA system. The design of such a system, and in particular the frame structure, clearly involves many inter-related decisions. In order to clarify the presentation, the first few sections below give an overview of the proposed design, and the subsequent sections provide more detailed information. Thus, Section A explains why centralized control was chosen for the system, and Section B introduces the proposed frame structure, with explanations of the different types of time slots within the frame and a brief justification for their presence. Further background is given in Section C which outlines modem configurations both for a user terminal and for a control station, and in Section D which discusses some pertinent modulation and coding considerations. Then, Section E describes the data slots, Section F describes the operation of a user terminal, and Section G the operation of the controller. Finally, Section H provides a recapitulation of the overall frame structure, including more specific data on the organization of the nine channels and the fraction of time devoted to the various functions.

A.   Control of Assignments

Conceptually, one of the simplest methods of realizing TDMA is for a terminal to transmit its message a block at a time at random times. If the terminal fails to receive an acknowledgment, it retransmits after a random delay. Such an asynchronous system (usually referred to as packet communication[4]) would be inefficient in throughput, however, and it would not come close to realizing the potential capacity of FLEETSAT-I as described in the previous section. By the same token, a synchronized system in which data slots are assigned on a dedicated basis would be straightforward to implement and might achieve a reasonable improvement in throughput if the slots were assigned to the largest users, but such a system would have very little of the flexibility desired in a FLEETSAT TDMA system. In order to achieve appropriate levels of efficiency and flexibility, it is therefore clear that the system must have

two attributes. First, there must be time synchronization, in which one terminal transmits a time reference, or clock for the entire system. Since the system cannot function without a clock, synchronization necessitates that selected terminals must be equipped with backup capability to transmit the clock, and that a scheme for handing over clock control be provided. Second, demand assignment is required in order to achieve positive control of preemption as well as flexibility of operation. Demand assignment can be realized with either centralized or distributed control. With centralized control, a particular terminal, designated the controller, is responsible for all circuit assignments, preemptions, and channel reconfigurations. With distributed control, each terminal contains a control algorithm and handles its own traffic by monitoring the satellite traffic and applying the algorithm. In principle, any scheme for centralized control could be implemented on a distributed basis by providing each terminal with the desired control algorithm.

For the FLEETSAT system, centralized control has a number of advantages and therefore is the basis of our proposed scheme. One of the more important reasons for having centralized control is its reduced requirements in terms of link reliability. Namely, with distributed control, each user terminal must monitor signaling information from a number of other users (at a minimum, all users in one channel) in order to determine system status, whereas with central control a single transmission from the controller contains the system status information required by a user. Moreover, the received P_r/N_o from a controller in a centralized system will be greater than that from a weak terminal in a distributed system--by about 4 dB when comparing a COMMSTA-submarine link with a submarine-submarine link. This benefit of centralized control is therefore twofold: signaling and system status information for a user depend only upon a single link, and that link is a relatively strong one. Another reason for utilizing central controller is that a FLEETSAT-I follow-on may itself contain such a controller. The demand assignment procedures of a FLEETSAT terminal working through a satellite controller would be quite similar to those through a terrestrial controller. Central control therefore

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will provide useful experience and a smooth transition for future systems. Other important advantages of central control include its more rapid and more positive capability to adapt to changes in the operating environment (e.g., traffic load, satellite malfunction), and easier control of multiple channels. Controller failure can be handled in the same manner as clock failure would be in any synchronous system.

Note that cost does not have a major impact on the method chosen because in either case some control is required at each terminal, and such control would be implemented in software (or microprogrammable hardware). Moreover, the software implementation not only implies that cost is insensitive to the complexity of the control algorithm, but it makes feasible the use of seemingly complex algorithms.

Because of its impact on overall system performance, the signaling to and from the central control station must be very reliable, more reliable in fact than data transmissions. Henceforth, we assume the following burst rates for control traffic:

- between controller and ships: 4 Kbps
- between controller and aircraft or submarine: 1 Kbps

Examination of Table 2-5 indicates that the above rates are conservative because (1) they allow the use of a fully equipped ship (rather than a COMMSTA) as a controller, and (2) with such a relatively weak controller they still provide at least 7 dB additional margin at E_b/N_o = 6 dB (assuming that coding is used for signaling information). It has been assumed, however, that aircraft and submarines signaling take place over a 28-dBw channel.

B.   Frame Structure Overview

Figure 3-1 shows a simplified diagram of the frame structure of a channel which carries control and signaling information in addition to data traffic. Each frame in such a channel contains a control slot, a request and ranging slot, and a number of data (i.e., traffic) slots. The control slot is transmitted by the central controller and contains the system clock,

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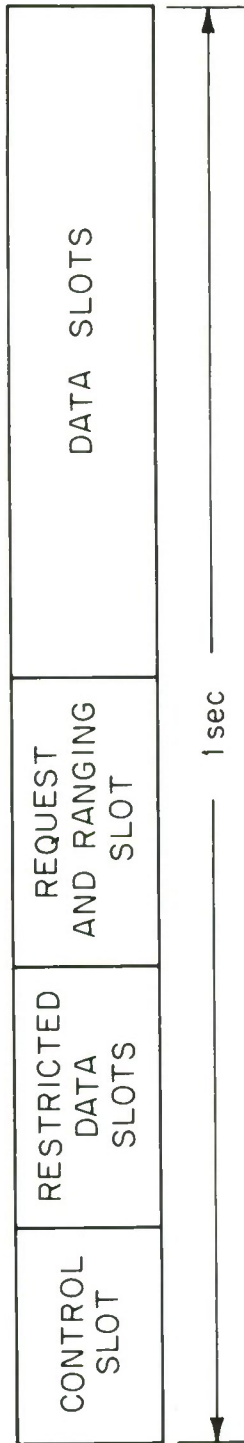
CONTROL SLOT EXPANDED

REQUEST AND RANGING SLOT EXPANDED

Fig. 3-1. Simplified frame structure for channel with signaling and control slots.

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information on system status, data slot assignments, and preemption commands. Each terminal using the system must monitor the control slot each frame. The request and ranging slot is used by terminals for transmitting requests for data slots and for initial ranging. A guard time of 1 msec is allowed between every pair of successive slots to prevent interference between users. The 1-msec value is consistent with the terminal turnaround times given in Sec. II-B-1 and is small enough that it does not introduce appreciable loss of throughput. The frame duration is 1 sec in accord with the constraints imposed by voice turnaround times, as discussed in Sec. II-C-1.

As explained later not all of the nine FLEETSAT channels handle control or signaling information; these channels can be used entirely for data transmission, although there are some restrictions on their usage. Transmissions other than data may be viewed as system overhead, and one design objective was, for a given set of requirements, to minimize the overhead while maintaining flexibility.

When a terminal is first switched on, it must perform frame synchronization in order to be able to receive data or control information. Frame synchronization, or obtaining downlink timing, involves locating a fixed framing sequence embedded in the control slot. Following this, a terminal determines its uplink timing, i.e., its propagation delay to the satellite. This is accomplished by transmitting a waveform in the ranging slot, which is wide enough to accommodate the waveform regardless of the actual terminal location. The central control station observes the waveform and, in the next control slot, notifies the terminal of the timing correction that is necessary. After applying the correction the terminal is permitted to request service and to participate in net traffic. With the ∿1-sec frames being considered, the ranging procedure significantly increases the throughput capacity of the satellite by decreasing the required guard time between slots.

In order to obtain a circuit, a terminal transmits a request for service in the shared request slots that form part of the ranging and request slot. If a conflict occurs in these shared slots, the request is re-transmitted.

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Shared slots are used because with the projected number of terminals using FLEETSAT, they require a significantly smaller fraction of a channel's capacity than do dedicated request slots. However, in order to guarantee a terminal's ability to make a request, a dedicated report slot is provided for each terminal in the satellite coverage area. The dedicated slot for a particular terminal occurs approximately once per minute and constitutes an important 'safety valve' in case of suddenly increased traffic or of the need to transmit a high precedence message.

When the controller recognizes a request for service, it responds either with an assignment or with an indication that the assignment cannot be made immediately. The assignment consists of a data slot in one of the channels, and may involve preemption of a slot already in use if all circuits are busy and if the request has high precedence. Rapid preemption is assured since all users monitor the control slot. The duration of the assigned data slot depends upon the data rate, a parameter determined by the weakest of the terminals that are using that slot.

Both downlink timing and uplink timing can drift because of relative motion between the terminal and the satellite, and because of inaccuracies in the terminal's (and the satellite's) frequency standards. For a shipboard terminal, in fact, inaccuracy in the standard may be the dominant cause of timing drift. Re-ranging must therefore be performed from time to time. If this re-ranging is performed about once every minute or two, then for the FLEETSAT equipment described in Section II, the chosen guard time of 1 msec will never be violated. Re-ranging is therefore accomplished by having each terminal use its dedicated report slot, even if no service request is desired. In other words, each terminal transmits a signal whenever its dedicated report slot comes up, and as with initial ranging, the controller responds with a timing correction.

The amount of overhead devoted to system control and signaling depends on such parameters as number of active terminals and calling rate, parameters that are not constant with time. Designing the system with the overhead needed

for maximum traffic or stress conditions would result in inefficiency under less than maximum conditions. Furthermore, it is imperative that the procedure for access and for preemption not collapse even if the actual operating environment is significantly worse than the specified heavy traffic or degraded channel conditions of Sec. II. To maintain the desired system response, then, while realizing the highest possible system efficiency, the fraction of the channel used for control is tailored to the current operating conditions by transmitting system status information in the control slot. Such information includes, for example, the number of request slots in a frame. With this scheme, the system can respond rapidly to changing traffic conditions, and a terminal initially accessing the system has immediate knowledge of system status.

The foregoing paragraphs show that the control slot data, transmitted by the central controller contains a variety of information: framing sequence, ranging and re-ranging timing corrections, circuit assignments and preemptions, and status information. The duration of this slot is roughly 100 msec. Because a terminal that is communicating must re-range occasionally and must listen for timing corrections and possible preemption commands, it is required that all terminals receive the control slot each frame and that all terminals be capable of transmitting in the request and ranging slot each frame. (That is, the design is more straightforward if this transmit capability is required every frame than if it is required, say only once every minute.) For full duplex terminals this requirement imposes no constraints, but for half duplex terminals, it means they cannot utilize the restricted data slots indicated in Fig. 3-1. (This is explained in more detail later.) The total duration of these restricted slots is equal to twice the greatest satellite-terminal propagation time plus the receive-transmit turnaround time of the terminal, approximately 280 msec in all. These restricted slots can, however, be assigned to full duplex or to multiple transceiver terminals, so they do not constitute system overhead.
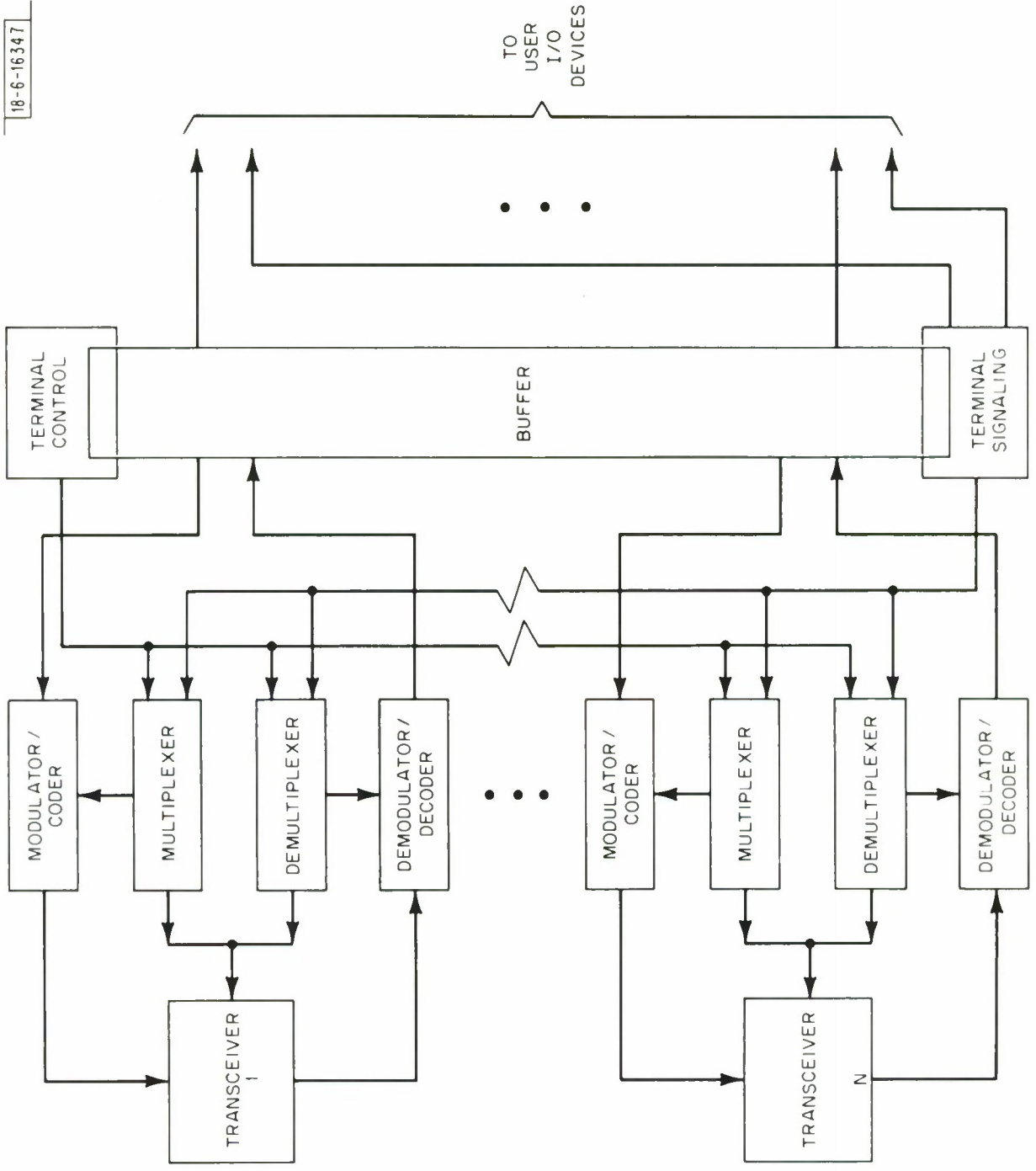
33

Fig. 3-2. Multiple transceiver FLEETSAT terminal configured as a user terminal.

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C.   Modem Configurations

The demand assigned TDMA scheme described here requires two related sets of equipment. One is the TACM (Terminal Access Controller and Modem) which is installed at each terminal, and the other is the system controller which is installed at selected locations that serve as backup control stations (a COMMSTA is the normal control station). A multiple transceiver installation for a user terminal is shown in Fig. 3-2. User I/O devices transmit data to and receive data from the data buffer at standard user data rates. The user data is coded and modulated, to be transmitted over the channel during the allocated time slot at the appropriate burst rate. Similarly, data received from the channel at a high burst rate are picked out of the incoming signal under control of the demultiplexer, and then demodulated, decoded, and sent to the buffer. In addition to such per-channel equipment as the decoder and demultiplexer,[*] each terminal requires control and signaling modules. The terminal control module handles frame synchronization, ranging, and timing corrections; the terminal signaling module handles user requests and responses to those requests ('assignment complete', 'busy', and so forth).

A terminal functioning as a control station is shown in Fig. 3-3. A qualified user can become a controller by adding a system control module. The control station receives service requests from user terminals and makes assignments, preemptions, timing corrections, and so forth. Since the control station also has its own users with communications needs, it retains the terminal signaling functions. However, the connection between controller signaling and terminal signaling is direct, rather than over the satellite channel.

The proposed system appears to the user to be a switched telecommunications network. The efficiency and flexibility of such a network are achieved through use of message oriented (contrasted with net oriented) requests and by automation of such control functions as initial acquisition and call

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[*]   In principle, these are considered per-channel devices, although in practice they may be shared among channels or even among transceivers.
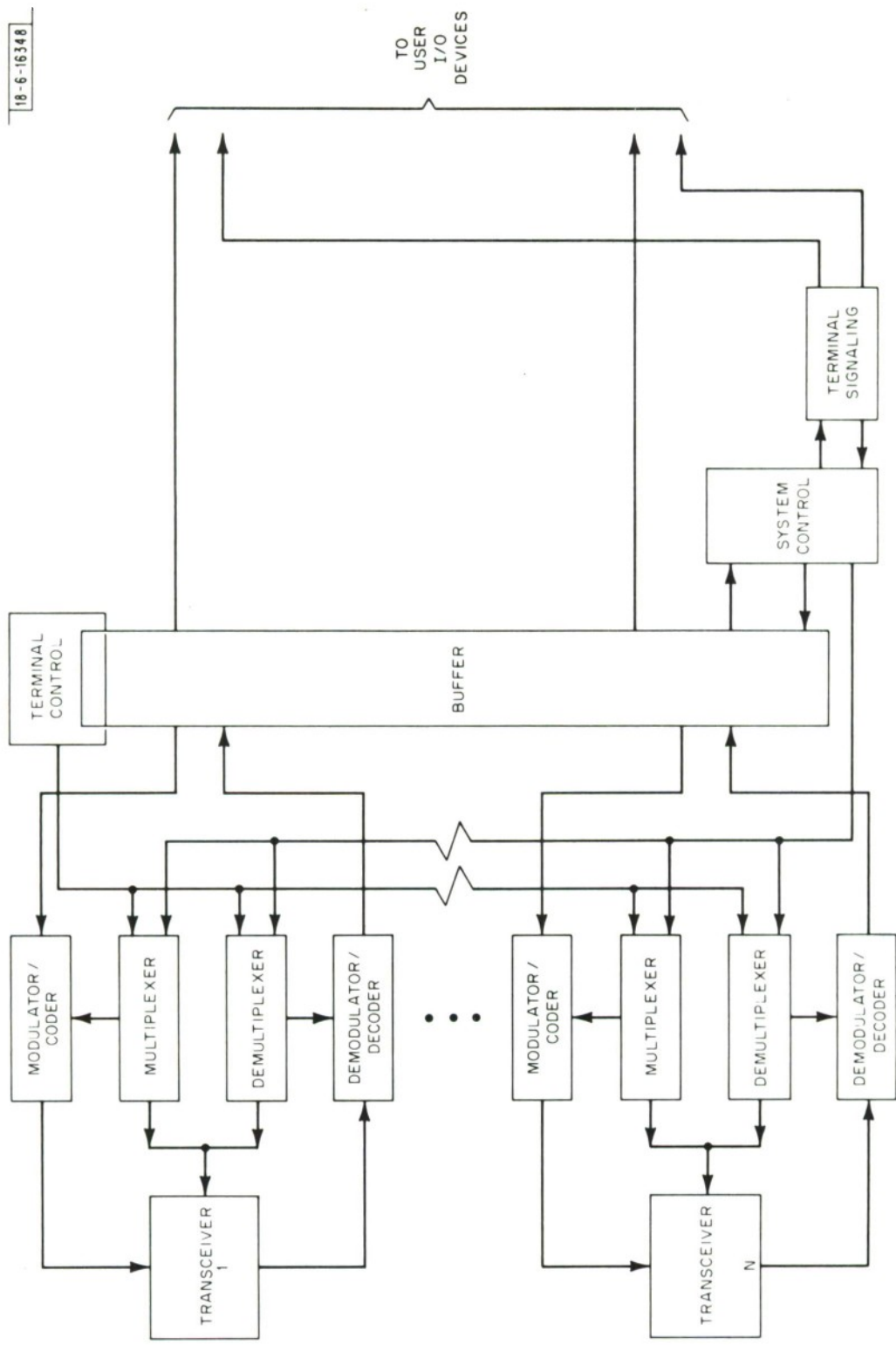
35

Fig. 3-3. Multiple transceiver FLEETSAT terminal configured as the system controller.

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TO
USER
I/O
DEVICES

TERMINAL SIGNALING

SYSTEM CONTROL

TERMINAL CONTROL

BUFFER

MODULATOR / CODER

MULTIPLEXER

DEMULTIPLEXER

DEMODULATOR / DECODER

MODULATOR / CODER

MULTIPLEXER

DEMULTIPLEXER

DEMODULATOR / DECODER

TRANSCEIVER 1

TRANSCEIVER N

setup. Control functions are automated to provide the user with call progress information and to minimize the need for user actions. A user initiates a request by specifying message precedence and the address of both the called terminal and net. The processing and transmission of the request and the handling of the controller response are also pre-programmed in the TACM.

D.   Modulation and Coding

Modulation and coding schemes for FLEETSAT-I should primarily be based on (1) robustness in providing the desired bit error probabilities over a broad range of expected operating conditions, (2) efficiency in the TDMA utilization of FLEETSAT links, many of which are bandlimited, (3) ease of extension to a degraded environment, and (4) cost effectiveness. Considerable analysis and simulation must precede the selection of a particular scheme, but some heuristic arguments can be given in connection with this preliminary design.

First, it is clear that because the RFI environment described in Sec. II may normally be present, some form of forward error control is necessary. Second, because many channels are bandlimited, signaling alphabets higher than binary should be considered. For the present discussion we will assume the use of PSK (phase-shift keying), and since preliminary investigations indicate that alphabets higher than quaternary are not likely to yield gains commensurate with their implementation problems, QPSK is considered. Prior to a final decision, however, the relative merits of other modulation schemes (in particular M-ary frequency shift keying) and of 8-ary PSK (especially for high power, bandlimited links) and offset QPSK will be studied. Finally, the most practical coding scheme available which satisfies the four criteria given above is a convolutional code with Viterbi decoding. It is worthwhile to note that even for bursts as short as those in the dedicated report slots, the performance gain (viz. the reduction in E_b/N_o for a given bit error probability) that can be realized with this scheme is still significant. Future investigations may in fact demonstrate that the data in these slots could either be transmitted at a rate higher than that assumed in Sec. A above or could be received with additional margin.

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As indicated in Table 2-5, some of the FLEETSAT-I links are power limited and some are bandlimited. To improve performance on power limited links, low rate codes can be employed, but on band limited links such codes may in fact degrade performance. At quadriphase symbol rates above approximately 0.5 symbol per second per Hz of bandwidth, the symbol energy outside the passband and the phase distortions near the band edges start to reduce the effective received signal energy. Above about 1 symbol per second per Hz this degradation is so severe that it cannot be offset by the expected coding gain. Thus, an uncoded link that is already bandlimited would probably not benefit (in terms of E_b/N_o) from rate 1/2 coding, although a higher rate code may yield some improvement and is in fact necessary to provide some protection against RFI.

Ideally, then, the code rate should be optimized to the channel parameters, but for illustrative purposes let us consider a rate 3/4 code. At this rate a 32-Kbps burst rate requires over 21K quaternary symbols per second, which, with the bandwidth of the FLEETSAT-I channels, results in about 1 symbol per second per Hz,[*] an operating point at which the bandwidth degradation is appreciable. The few strongest links--indeed, those that carry a significant fraction of the traffic--have sufficient signal strength to operate at this rate despite the degradation. Most links, however, must operate at lower burst rates. At 16 Kbps, the rate 3/4 code requires only about 0.5 symbol per second per Hz, a value which does not result in much degradation and can therefore take nearly full advantage of the performance gain offered by the code.[**] With a constraint length 9 convolutional code, soft decisions, and Viterbi decoding, the power limited data rates indicated in Table 2-5 for E_b/N_o = 6 dB are therefore valid for a bit error probability of 10^{-5} [5] (E_b/N_o = 6 dB allows some margin in addition to the 6-dB margin in each link). For 16-Kbps voice traffic which requires only a 10^{-2} bit error rate, the tabulated data rates can almost be doubled.

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[*] The nominal transponder bandwidth is 25 KHz. The center frequency is accurate to $\pm$ 1 kHz, which in effect reduces the bandwidth to 24 KHz. Finally, if 1 kHz is allowed for Doppler shift, the resultant bandwidth is 22 KHz.

[**] It may, of course, be advantageous to support several code rates, basing the actual rate upon the effective (P_r/N_o) of the link. Such a procedure would increase satellite throughput at the expense of greater complexity of implementation.

Unfortunately, coding and link margin together are not sufficient to protect against strong ionospheric scintillation. On terminal-to-terminal links, some form of error detection coding superimposed upon the convolutional code would enable ARQ (automated repeat requests) to be made if a received block of data were not correctly decoded. Although an ARQ procedure would decrease the effective throughput rate, it possesses the important advantage that the mode of operation need not be changed if scintillation occurs. Also, the procedure is helpful in eliminating errors even during normal channel conditions. With multi-terminal (e.g., broadcast) type transmissions, however, ARQ is both cumbersome and inefficient. In this case, a reasonable method of maintaining communication during scintillation is to provide an additional 6 dB link margin and to interleave the transmitted data in order to evenly distribute the symbols that are caught in scintillation fades [3]. To provide adequate protection, the interleaving must be over periods of about 20-30 sec. (Observe from Table 2-5 that for a link as weak as COMMSTA-to-submarine, 6 dB additional margin still permits throughput in excess of 1200 bps). The combination of coding, extra margin, and interleaving should provide sufficient protection against all but the most severe scintillation. Further study will show whether it is more practical to employ different techniques during scintillation for terminal-to-terminal and for multipoint traffic, or whether all terminals should modify their communication format. Unfortunately, in either case the delays introduced by ARQ or by interleaving are sufficient to severely hamper voice communications under worst case conditions.

Although the degradations introduced by multipath (and by antenna motion) are not as severe as those with worst case scintillation, the techniques described above, if implemented for scintillation protection, could also be invoked in the presence of multipath. Thus, interleaving, ARQ and even increased margin allowance could, if necessary, be applied to counter the effect of multipath interference.

To combat RFI, any forward error correction scheme can be aided with some form of pulse blanking, performed on either analog or digitized signals. In any case, the receiver blanks the input whenever it exceeds a threshold

value. Symbols coincident with an RFI pulse will thus be considered as
erasures. Since on the average the erasures constitute only about 5% of the
received data, the redundancy needed to fill such erasures represents only a
small reduction ($\sim$5%) in the effective data rate.

E. Data Slots

Data slot durations are based on the user I/O rates and the burst rate.
The user I/O rates (viz. the data rate required by such user equipment as
vocoders, externally buffered message systems, or teletypes) range from 75 bps
to 32 Kbps. For efficiency, data at low I/O rates (below 2.4 Kbps, say) are
buffered internally and treated by the system as 2.4 Kbps user data. This
buffered rate is called the "effective data rate" in this report. The effective
rate equals the user rate for user rates exceeding 2.4 Kbps.

In order to time division multiplex data from many users, the data must
be transmitted in bursts having rates much higher than the effective rates
of the users. A block of data corresponding to one frame at the effective user
rate then requires only a fraction of a frame for transmission at the higher
burst rate. The burst rate at which the user data is transmitted through the
channel is based on the effective P_r/N_o of the link*. In accord with the
discussion in the previous section, the maximum burst rate considered is 32 Kbps.
This value is presumed feasible for a bandlimited link which has an effective
P_r/N_o of 54 dB or greater. The minimum data slot duration would then result
from the minimum effective data rate (2.4 Kbps) transmitted at the maximum burst
rate (32 Kbps). For one-second frames, this minimum data slot duration is
75 msec, which we define to be the reference data slot duration. Slot widths
for effective data rates other than 2.4 Kbps or for links with effective P_r/N_o
less than 54 dB are given by the expression:

$$\text{Slot width (msec)} = 75 \text{ msec} \times \frac{\text{effective data rate}}{2.4 \text{ Kbps}} \times \xi$$

where ξ is a "data slot expansion factor." Figure 3-4 illustrates the behavior
of ξ as a function of P_r/N_o. For P_r/N_o less than about 50 dB, the curve is
linear since the link is power limited. The nonlinearity in the curve at

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* The burst rate also depends on the modulation format, the code, and the desired
error rate. For this discussion, we assume QPSK modulation, a rate 3/4 code,
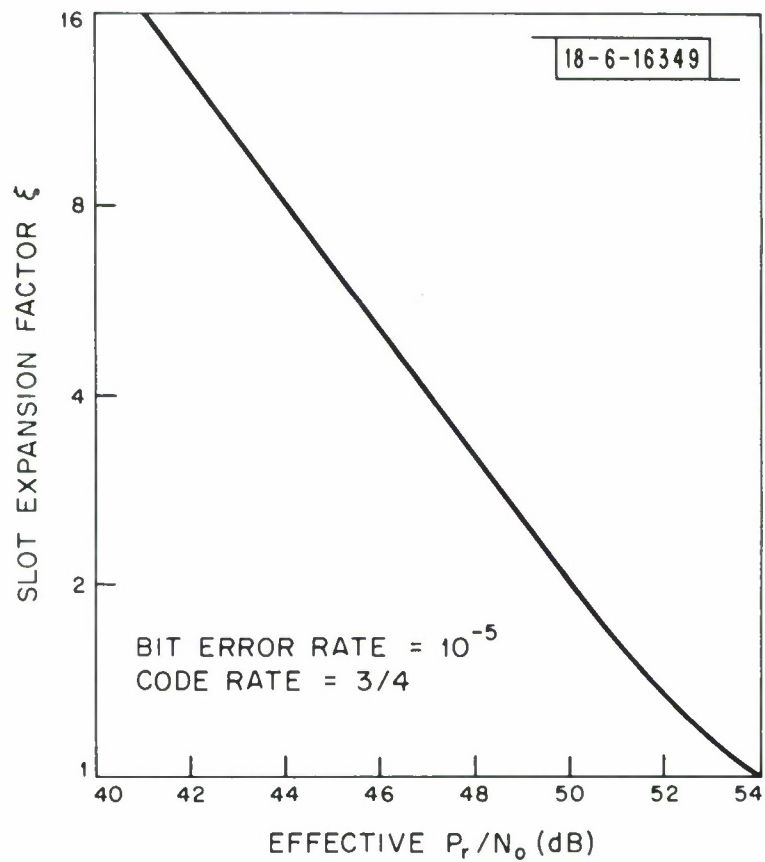and a 10^{-5} bit error rate.

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Fig. 3-4. Data slot expansion factor as a function of effective P_r/N_o.

higher values of P_r/N_o results from the effects of bandlimiting. The data slot width for an effective data rate of 4.8 Kbps on a link with P_r/N_o of 50 dB (fully equipped COMMSTA-to-ship) would, for example, be

$$75 \text{ msec} \times \frac{4.8 \text{ Kbps}}{2.4 \text{ Kbps}} \times 2 = 300 \text{ msec} \quad .$$

There are six standard effective user data rates considered in this report: 2.4, 4.8, 8, 9.6, 16, and 32 Kbps. The design provides, say, eight burst rates between 2.4 and 32 Kbps. Since in general, the burst rate must exceed the data rate, 32 different slot widths, from 75 msec (for 2.4 Kbps data at 32 Kbps burst rate) up to 1 sec (32 Kbps data at 32 Kbps burst rate) suffice. Each data slot is specified by its width, its start time in the frame, and the channel. The frame is divided into milliseconds to provide gradations consistent with the one millisecond guard times. Hence, 19 bits are used to specify a data slot; 5 bits for the width, 10 bits for the start time and 4 bits for the channel.

In addition to data slots, traffic which relies on ARQ must have acknowledgment slots. Two strategies for deriving such acknowledgment slots seem promising. One strategy uses every n-th data slot for acknowledgment, and the other uses a separate slot within each frame for the reverse channel. The first strategy is the simpler of the two in ease of assignment, but requires more overhead. In either strategy, acknowledgment takes place over the past 30-60 frames. An acknowledgment on the data in each received frame would then be made 30-60 times. Since scintillation fading is roughly inde-pendent from one few-second period to another, with very high probability the acknowledgment for a data burst would get through successfully at least once.

F.   User Terminal Operation

1.   Control Functions

a.   Frame Synchronization

The first step in using the system is for a terminal to synchronize with the downlink frame structure. Frame synchronization is achieved by recognizing a fixed bit sequence within the control slot. Prior to recognizing this framing sequence, or clock, a terminal must acquire the frequency and

symbol timing of the control slot burst, a feat which can be difficult in a TDM environment because the received data stream comprises bursts from a number of different terminals, none of which are in exact synchronization. To overcome this difficulty, a terminal performing initial acquisition could either track symbol timing and frequency from burst to burst, or it could estimate these parameters anew whenever the detected energy, measured over some short interval, drops below a threshold. In either case, acquisition of the framing sequence in enhanced if the sequence is placed near the end of the control slot, thereby ensuring that the timing and frequency of this burst have been determined prior to receipt of the clock.

To actually recognize the framing sequence, a correlation technique may be used. Simple estimates can be obtained on the length of the sequence, on the probability of missed acquisition, and on the probability of false acquisition (i.e., of interpreting some non-framing sequence to be the framing sequence) if it is assumed that the received data is in one synchronous stream (rather than in a series of bursts) and that hard decisions are made on each received symbol. Both of these simplifying assumptions should yield conservative estimates. The analysis below also assumes steady channel conditions (e.g., no scintillation). In the frame synchronization scheme hypothesized for this discussion, the terminal continuously searches for an exact match between the received data and the known framing sequence. Acquisition is said to occur if two matches separated by one frame time are found. In any two-frame interval the probability that the framing sequence will be detected is

$$P(\text{detect}) = P(\text{recognize framing sequence in both frames})$$
$$= (1-p)^{2m}$$

where p is the bit error probability and m is the number of bits in the framing sequence. In the cases of interest $(mp) \ll 1$, so the above expression reduces to

$$P(\text{detect}) \approx 1 - 2mp$$

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False detection occurs if an m-bit sequence in the non-clock portion of the data stream is identical to the framing sequence in corresponding portions of both the first and second frames. If there are N bits in a frame, then the probability of this event is

$$P(\text{false detection}) = [(N-1)2^{-m}] \, [2^{-m}]$$
$$\approx N \, 2^{-2m}$$

and this event is independent of the detection probability.

Correct acquisition takes place if the framing sequence is detected and if no false detection occurs; false acquisition occurs if the framing sequence is not detected and if false detection occurs; in other cases, the acquisition attempt must be repeated in the succeeding two frames.

Assume for this discussion that the sequence is transmitted using differential PSK modulation and no coding, and that the received symbol energy to noise density ratio E_s/N_o = 10 dB (this is 4 dB more than the E_b/N_o assumed for coded transmissions and allows at least 3 dB margin in addition to the link margin). Then $p \approx 0.2 \times 10^{-4}$ with incoherent detection, so that for N = 4000 bits (4 Kbps with a 1-sec frame) and m = 14 bits, we have for any two-frame interval:

P(correct acquisition) > 0.999
P(false acquisition)   < 10^{-8}
P(retry)   < 0.001

(If any of the traffic in the frame were at a rate higher than 4 Kbps, the false acquisition probability would decrease.) Thus, 14 bits are sufficient to achieve satisfactory performance even if there is some degradation from the above values. It should be noted that the control slot will also contain a time-of-day clock sequence (for synchronizing cryptographic equipment). Since this clock changes in a known manner from frame to frame, it can be used in

addition to the framing sequence to assist in achieving frame synchronization, thereby improving the performance of a given length sequence. A terminal continuously verifies its frame synchronization in the process of monitoring the control slot each frame.

b. Ranging

Having achieved frame synchronization, a terminal is capable of receiving traffic. A terminal closest to the satellite (i.e., directly beneath the satellite) receives this traffic after a transmission delay of 119 msec, whereas for one on the edge of the coverage area (0° look angle), the delay can be as great as 140 msec. Since this same 21-msec difference in transmission times also applies to uplink transmissions, and since it is assumed that a terminal has no prior information regarding its position relative to the satellite, interference between transmitting terminals can be avoided only if the system either (1) provides 42-msec guard times on each burst of data, or (2) enables the terminals to more accurately determine their transmission delay, reducing the guard time in proportion to the remaining range error. Although the former method has the advantage of ease of implementation, it wastes a considerable fraction of the channel capacity if the duration of the data bursts is a few hundred milliseconds or less. For this reason, the proposed scheme includes a ranging function by which the terminal can determine its transmission time to the satellite.

One ranging slot is provided in each frame,[*] and a terminal that must range transmits a known waveform in that slot. The controller examines the ranging slot for this waveform, computes the timing and frequency errors if the waveform is detected, and transmits the necessary correction to the terminal. The ranging computations are performed by the controller rather than by the terminal listening to its own repeated transmission because some

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[*] Following the framing sequence in the control slot are the frame parameters which provide the terminal with information on the frame structure. If traffic conditions necessitate, it would thus be possible to modify the location or duration of the ranging slot.

terminals do not have sufficient P_r/N_o to carry out the latter procedure and because the FLEETSAT-II satellite will not be a simple repeater (i.e., a ranging calculation will be performed in the satellite itself). Centralized ranging calculations also result in somewhat simpler terminals.

In order to obtain an estimate of the required duration of the ranging signal, techniques similar to those used with radar systems can be applied. Thus, for a known waveform having both time and frequency uncertainties, the variance at high SNR in the measurements of each of these quantities is given by [6]

$$\sigma_\tau^2 \approx \frac{1}{(2E/N_o)\beta^2} \qquad (3-1)$$

$$\sigma_f^2 \approx \frac{1}{(2E/N_o)(2\pi\alpha)^2} \qquad (3-2)$$

in which E is the total received energy of the waveform, and β and α are the rms bandwidth and the rms duration, respectively, of the waveform. Let E_s and T_s denote the energy and duration of one symbol in the waveform. Then $E=nE_s$, and for the signaling rates under consideration, $\beta \geq 2\pi/T_s$. A reasonable goal for the timing accuracy required in ranging is based upon limitations of the equipment to be used with FLEETSAT-I as well as upon the overall TDMA frame design. As noted earlier, equipment limitations necessitate guard times of $\sim$1 msec for any burst. Thus, range accuracy must be maintained to within $\pm$500 µsec. On the other hand, as discussed in the following section, the timing drift between ranging corrections could, in an extreme case, be expected to be as great at 240 µsec. For initial ranging, then, an accuracy on the order of $\pm$100 µsec is adequate. For sufficient confidence on this accuracy we require that $3\sigma_\tau \leq 100$µsec. Substitution in (3-1) gives

$$n \geq 1.1 \times 10^7 \frac{T_s^2}{(E_s/N_o)}$$

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At the lowest signaling rate, $T_s = 1$ msec, so that for $E_s/N_o = 10$ (as assumed for frame synchronization), only two symbols are required.

A measure of the required frequency accuracy can be obtained by assuming in-phase and quadrature correlation over the duration $T = nT_s$ of the waveform, with incoherent combining of the results. A frequency error Δf then yields the degradation $[\sin(\pi T\Delta f) / (\pi T\Delta f)]^2$. For less than 0.5 dB degradation, $(T\Delta f)$ must be less than 0.19, and so we require $3\sigma_f < 0.19/T$. If the modulation is assumed to be binary PSK, then the rms duration is $\sqrt{T^2/3}$, and substitution in (3-2) yields

$$n > \frac{10}{(E_s/N_o)}$$

showing that two symbols are also adequate for frequency acquisition.

The duration of the required ranging waveform as derived above appears optimistically brief and deserves some additional verification. A different approach to estimating the required duration will therefore be given. The duration of the ranging slot is equal to the duration of the ranging signal plus twice the guard time (42 msec). For 100 μsec accuracy, there are $42 \times 10^{-3}/10^{-4} = 420$ possible starting times that must be examined, and hence $\log_2(420) \backsim 9$ bits are needed to specify the start time. Similarly, the required frequency accuracy is $(0.19/T)$, equivalent to $\log_2(2f_{off}/(.19/T))$ bits, where f_{off} is the possible frequency offset ($\pm$Hz) between the received and the locally generated signals. For an aircraft, f_{off} may be as great as 700 Hz (see Table 2-2). Assume that the ranging signal contains three symbols, each lasting 1 msec, with E_s/N_o of 10, so that the frequency information represents $\log_2(22) \backsim 5$ bits. Then the ranging signal has a total E/N = 30 and must provide 14 bits of information. If this 14-bit message were orthogonally coded, the received E_b/N_o would be 30/14=2.1, yielding an error probability less than 10^{-3} with incoherent reception, thus indicating that a 3-symbol ranging sequence is adequate. (Similar calculations apply for other platforms.)
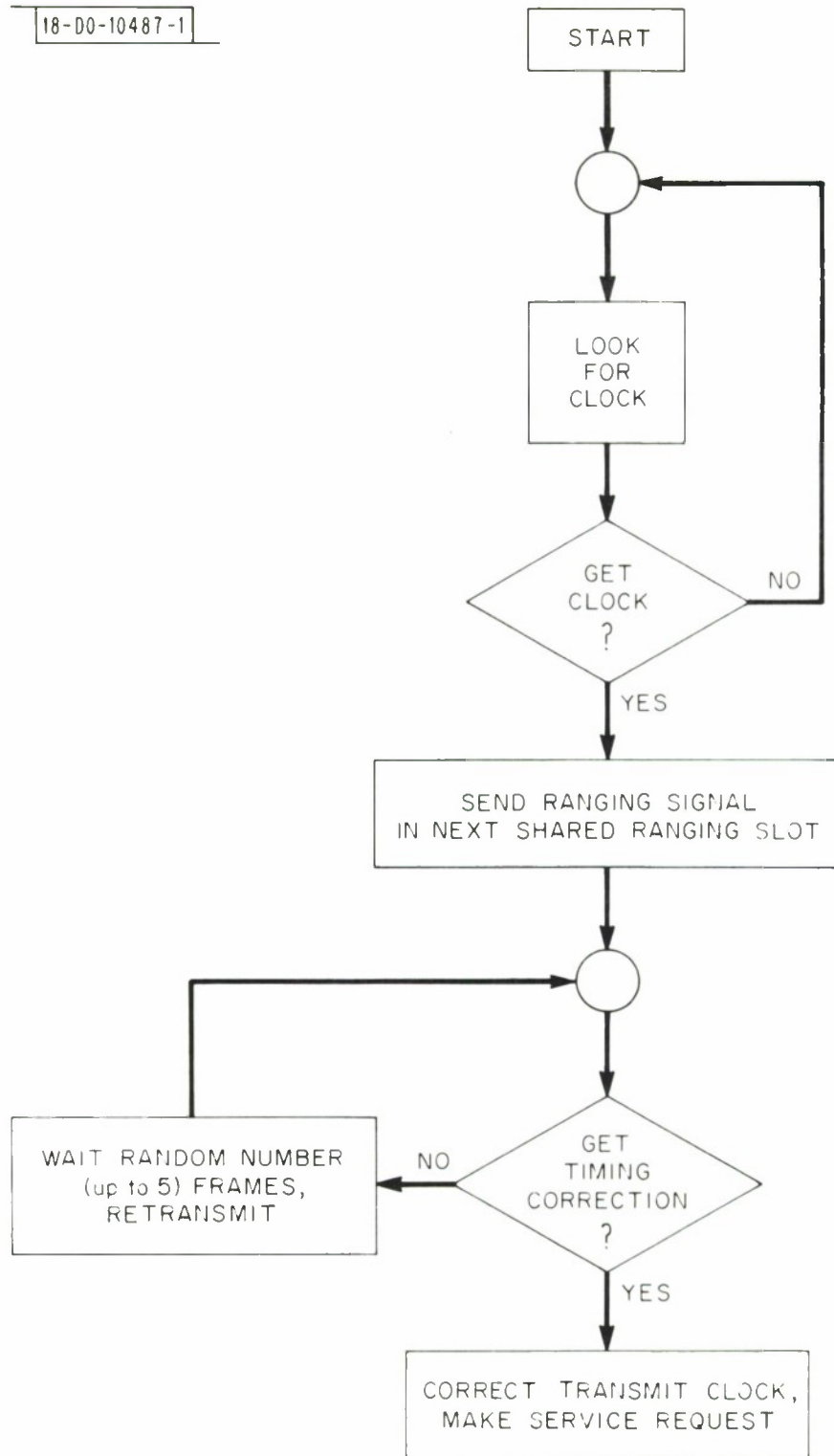
Fig. 3-5. Flow chart of initial system acquisition.

Thus, both of the above arguments indicate that with the assumed E_s/N_o, only a few symbols are needed for ranging; we shall conservatively assume that 6 symbols are used. Added to these is a 9-bit sequence specifying the terminal address (which will aid in the acquisition), resulting in a 15-bit sequence. The above calculations assumed a symbol rate of 1 Kbps, consistent with that of the lowest rate terminals, but the results are equally valid for ships which can signal at 4 Kbps maintaining E_s/N_o = 10 dB. Ranging signals are thus 15 msec long for aircraft and submarines, 5 msec for ships. As explained later, separate ranging slots are provided for the two types of terminals.

The initial acquisition procedure, flow charted in Fig. 3-5, is therefore as follows: After obtaining frame synchronization (or whenever timing may be in error by more than 500 μsec), a terminal transmits its 15-bit ranging signal in the next ranging slot (duration 46 or 57 msec). The controller computes the timing correction and transmits it in the next control slot. If the terminal does not receive the timing correction--an event that could occur either because of interference from another ranging terminal or because of disturbed channel conditions--then the terminal waits a random number (1 to 5) frames to re-attempt the ranging. The random re-transmission scheme is used to lessen the probability of repeated conflicts in the (shared) ranging slot. The timing correction from the controller is 22 bits, of which 9 are the actual correction, 4 identify the word type, and 9 identify the terminal.

A slight modification to the ranging slot described above is to increase the duration of the slot, thereby reducing the likelihood of interference between ranging signals from different terminals. Actually, if the increase were equal to one or more times the duration of a ranging signal, then two or more terminals from the same locality could be accommodated in the same slot without interference. The potential benefit of this approach is that (1) it might reduce the overhead by eliminating the need for a separate ranging slot in the ship channel (cf. Fig. 3-12); and (2) the ranging slot can be expanded under heavy traffic conditions without incurring much of a penalty. This approach will therefore be investigated in the next phase of this study.
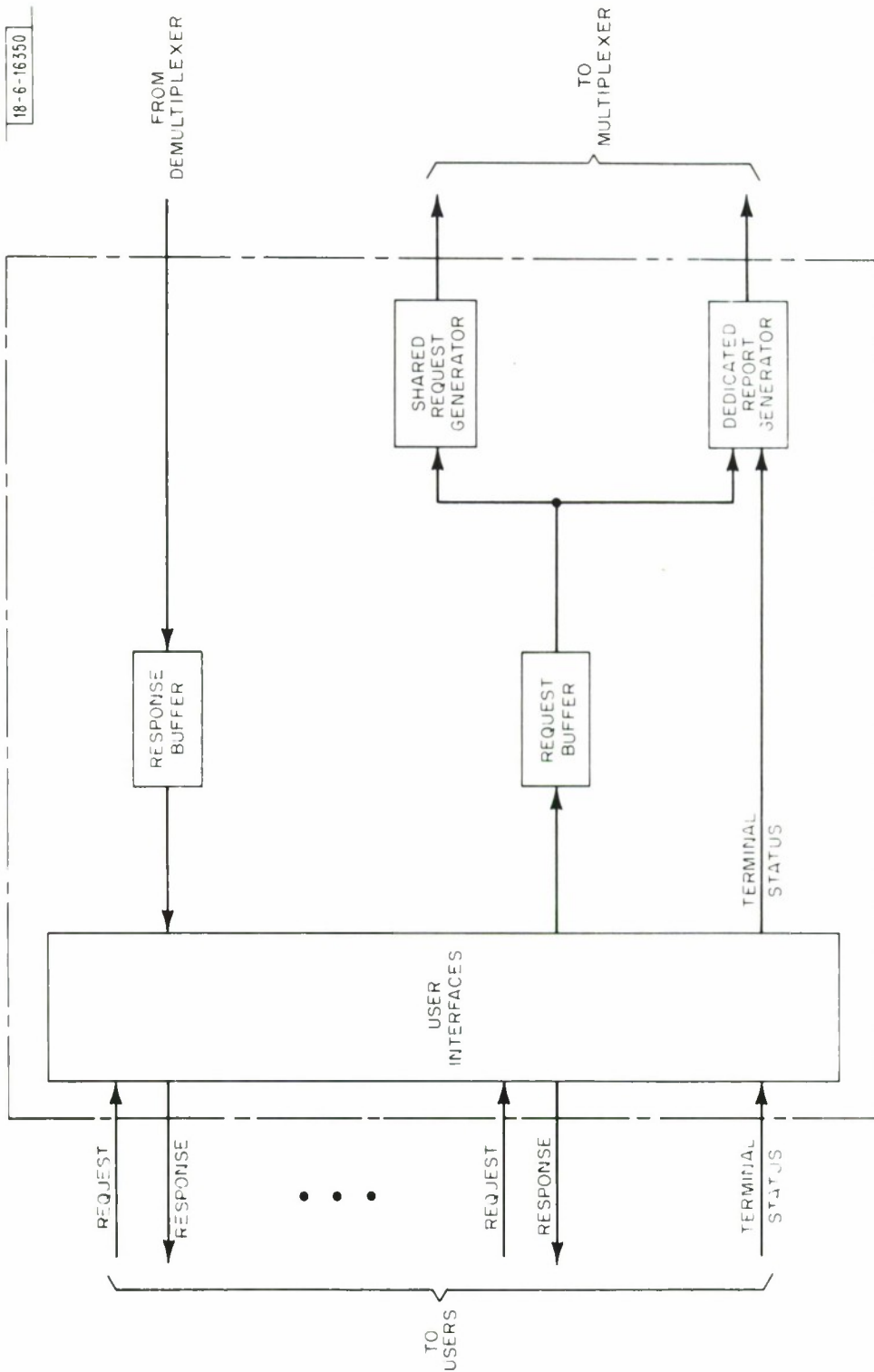
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Fig. 3-6. Functional diagram illustrating terminal signaling.

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c. Range and Clock Drift Corrections

After frame synchronization and ranging have occurred, a terminal is capable of receiving and transmitting without interfering with other users. However, a terminal's timing will drift because of motion of the terminal (range drift) and because of inaccuracy in the terminal's frequency standard (clock drift). A terminal can correct for range drift by monitoring the framing sequence and calculating its drift ΔT with respect to that sequence. The terminal then changes its downlink reference by ΔT and changes its uplink reference by $-\Delta T$. Since the total drift between frames is much smaller than the duration of a control slot symbol, there is no re-acquisition difficulty in monitoring the data in that slot.

With the above technique, however, inaccuracies in a terminal's time reference are interpreted as positional changes, and these timing updates, although proper for downlink timing, are of the wrong polarity for uplink timing. Clock drift must therefore be corrected by an independent technique. Namely, the terminal transmits a signal in its dedicated report slot, the controller monitors this signal and, as in the initial ranging operation, computes the timing correction and informs the terminal in the next control slot. Since dedicated report slots occur about once per minute, the maximum clock drift between re-ranging attempts is $\sim$60 µsec (cf. Table 2-2). But as noted above, the range drift corrections effectively double the clock drift error, which therefore could be as great as 120 µsec after one minute. Nevertheless, even if degraded channel conditions cause the loss of a clock drift correction, the accumulated error is well within the 0.5-msec guard time allowed on either end of a burst.

2. Terminal Signaling

After receiving the uplink timing correction from the controller, the terminal is ready to make service requests and participate fully in net traffic. Figure 3-6 shows a functional diagram of terminal signaling. A user enters a service request into the request buffer via the user interface. The request will be transmitted either in the dedicated or in the shared request slots,

as will be discussed shortly. The response which returns from the controller is subsequently sent to the user. The user also has some indication of terminal status; that is, how much terminal capacity is in use and with what precedence traffic, and how much capacity remains.

a. Shared Request Slots (Ships)

The design decision on the use of shared request slots or dedicated request slots is based on user requirements, on projected traffic statistics and number of terminals, and on desired system efficiency. With dedicated request slots, each terminal is assigned a slot which recurs periodically, every K frames, say. As long as all terminals remain synchronized, no conflict can occur, and the maximum waiting time to send a request equals K frame times. The calling terminal's address is implicit in the slot location. Hence the terminal need only identify the called terminal (9 bits), the net (7 bits) and such characteristics of the call as precedence, data rate and approximate length ($\sim$9 bits) for a total of $\sim$25 bits. With shared slots, each frame contains a number of slots which any terminal may use. Conflicts, of course, can occur. A shared request slot must contain, in addition to the 25 bits of the dedicated slot, the calling terminal's 9-bit address, for a total of 34 bits.

To compare the efficiencies of dedicated and shared slots, we consider shipboard terminals (the numerically largest category) and recall from Sec. II that the desired system response time is on the order of three seconds. With a 4 Kbps transmission rate and guard times of 1 msec on each burst, the fraction of a one second frame required by dedicated slots with the nominal 150 ships in a coverage area is

$$\eta_D = \frac{150 \text{ ships x 1 slot/ship x } (\frac{25 \text{bits}}{4 \text{Kbps}} + .001 \text{ sec})}{3 \text{ seconds}}$$

$$= 0.36$$

in which the response time is taken as the period of a particular dedicated
slot. Although this 36% overhead applies only to one of the nine channels,
it represents just a part of the total system overhead. Furthermore, if a
channel disturbance adversely affects the request, three seconds are added to
the response time, and if the number of ships increases, the overhead (or the
response time) increases proportionately. Thus, for the specified system
parameters, dedicated slots are feasible but have significant disadvantages.

Response time calculations for shared slots are much more involved
than for dedicated slots. As an initial simplification, we make the
conservative assumption that if a conflict occurs in one of the shared slots,
then no request is recognized and all contenders must re-transmit. The
interval between re-transmissions must be chosen randomly in order to avoid
continued conflicts. Now suppose that k shared slots are provided in each
frame, that there are requests from r different terminals and that each
request is transmitted ℓ times in each frame. For one of the r users, the
probability of success is simply the probability that at least one of the ℓ
slots chosen at random is not chosen by any of the r-1 other users. (This
neglects the possibility that the controller will not correctly receive the
request, an event of much lower probability that a conflict.) The probability
that any one of the ℓ slots is used by someone else is $1 - (1-\ell/k)^{r-1}$, so
that the probability that all ℓ are used is $[1-(1-\ell/k)^{r-1}]^{\ell}$. The probability
of success, then, is

$$P_S = 1 - [1-(1-\frac{\ell}{k})^{r-1}]^{\ell} \; .$$

Determination of the exact dynamic behavior of a system with shared
request slots is at best a difficult problem. The following approximation
suffices for a preliminary design and will eventually be sharpened by simula-
tion and further analysis. Let λ be the rate (requests/frame) at which new
requests arrive. Then the total request rate $r = \lambda+f$ where f is the failure
rate for requests. For a steady state solution to exist, the number of new
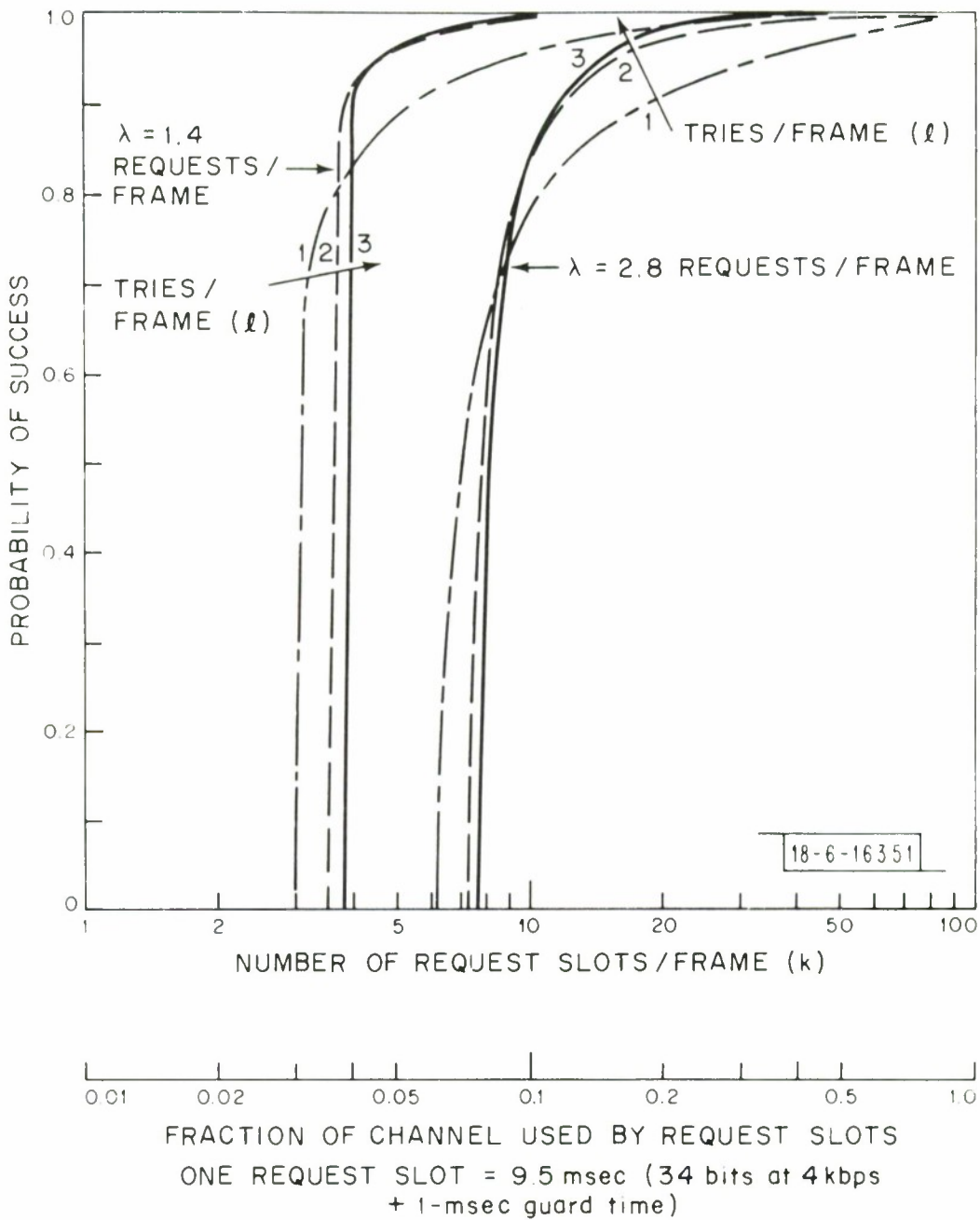requests λ must equal the number of successes. Under the simplifying assumption

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Fig. 3-7. Probability of success for a terminal making a service request as a function of the number of request slots in a frame.

that both the new requests and the failures are uniformly distributed in time, $\lambda = (\lambda+f)P_S$, or

$$\frac{\lambda}{\lambda+f} = P_S$$

$$= 1 - [1-(1-\frac{\ell}{k})^{\lambda+f-1}]^{\ell}$$

P_S can be made close to 1 by making k, the number of slots, large. Figure 3-7 shows the relationship between P_S and k for λ = 1.4 and 2.8 requests/frame,[*] and for ℓ = 1,2 and 3. Although the equation plotted in the figure does not take the real (non-uniform) distribution of requests into account, the calling rates are thought to be somewhat extreme. Hence, the curves provide a sufficient basis for this preliminary design.

The design response time is 3 seconds with, say, 99% confidence. Response time for a request made in a shared slot is the time for a request to successfully reach the controller plus the time for the controller response to reach the user. The user transmits a request at random in ℓ of k slots in a frame. If the controller receives at least one of the ℓ requests, it responds in the next control slot. If, however, the user does not receive the response, the user retransmits, again at random, in ℓ of k shared request slots in the next frame. It is easy to see that the response time in seconds is less than or equal to the number of frames in which the request is transmitted plus one. Therefore, a 3-second response could be achieved by transmitting in one frame, failing, then retransmitting successfully in the next. For 3-second response time with 99% confidence, then P_S = 0.9 for each frame. Note in Figure 3-7 that for P_S = 0.9, multiple requests in each frame require fewer slots than do single requests.

In particular, with a calling rate of 1.4 calls per second, the desired response could be achieved by supplying ∿4 shared slots per frame and by having a terminal make 3 requests at random in the frame. However, as shown in the

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[*] Since the frame duration is one second, per-second and per-frame values are used interchangeably.

figure, 4 slots would be so close to the knee of the curve that even a slight temporary increase in the calling rate would drastically reduce P_S and degrade system performance accordingly. One solution would be to have the controller estimate the request rate and vary the number of request slots in order to maintain a relatively constant P_S. However, from both a designer's and a user's point of view it is not desirable to modify the frame format frequently. A preferable solution is to provide a comfortable margin at the nominal operating point. For example, ten shared slots per frame would provide some protection against traffic increases and would also increase the confidence level for a three second response under nominal conditions. Moreover, ten slots use only 9% of one 25-kHz channel, negligibly decreasing the total communications capacity that would have been available with four slots.

Under actual operating conditions when the statistical nature of the traffic becomes important, the performance predicted by the above analysis may be somewhat optimistic. Nevertheless, the results do indicate that response times equalling those of dedicated slots can be achieved with much less expenditure of channel overhead. Further, if one or even two of the requests are lost because of channel disturbances, the degradation is not severe, being only one or two seconds. Ten shared slots also provide enough of a cushion to handle 2.8 calls per second with 90% confidence of a three-second response. This calling rate, double the nominal, is the mean rate during heavy traffic, as given in Section III-C-2. For continued operation under heavy traffic, the number of slots would, of course, be increased. Sixteen slots, occupying 15% of one channel, give a three-second response with greater than 99% confidence.

b. Dedicated Report Slots (Ships)

Although shared request slots have been shown to achieve a particular average level of performance with less system overhead than dedicated slots, they suffer from one major drawback: because of the statistical nature of the service requests (or because of a temporary increase in the level of traffic) the probability of conflict can increase enough to cause an undesirable increase in system response time. With the scheme just described, for example,

if the rate of new requests approaches about 0.25 calls per request slot, then the response time approaches infinity. This problem is typical of queueing systems with fixed resources. Namely, for a given amount of system capacity, waiting times increase sharply when new service requests increase above a certain level. The capacity can, of course, be increased, but only at some expense and with the penalty of reduced efficiency during normal operating conditions.

Fortunately, a relatively simple solution exists for the FLEETSAT-I system, which has a moderate number of terminals. Each terminal is provided with an occasional dedicated time slot, which actually serves a number of purposes:

1. If the dedicated slot comes up within a frame or two after a user enters a request, then it, rather than the shared slots, is used.

2. If some predetermined number of conflicts occurs, the shared slots are abandoned, and the request is made in the dedicated slot.

3. A terminal with low precedence traffic can normally wait for the dedicated slot to send circuit requests.

4. Periodic messages on terminal and equipment status are transmitted to the controller as necessary in these slots. (Examples of such messages are "relinquishing circuit in channel 5" and "partial transmitter failure.")

5. As noted earlier, signals are transmitted in the dedicated slots to enable the controller to update a terminal's uplink timing.

6. The continued absence of any energy in a terminal's dedicated slot informs the controller that either the terminal has become inactive or it has experienced a malfunction.

Because these slots handle more than requests alone, they will be referred to as dedicated report slots. Three such slots per frame, occupying a total of 22 msec, yield a maximum response time of 50 seconds for any terminal.
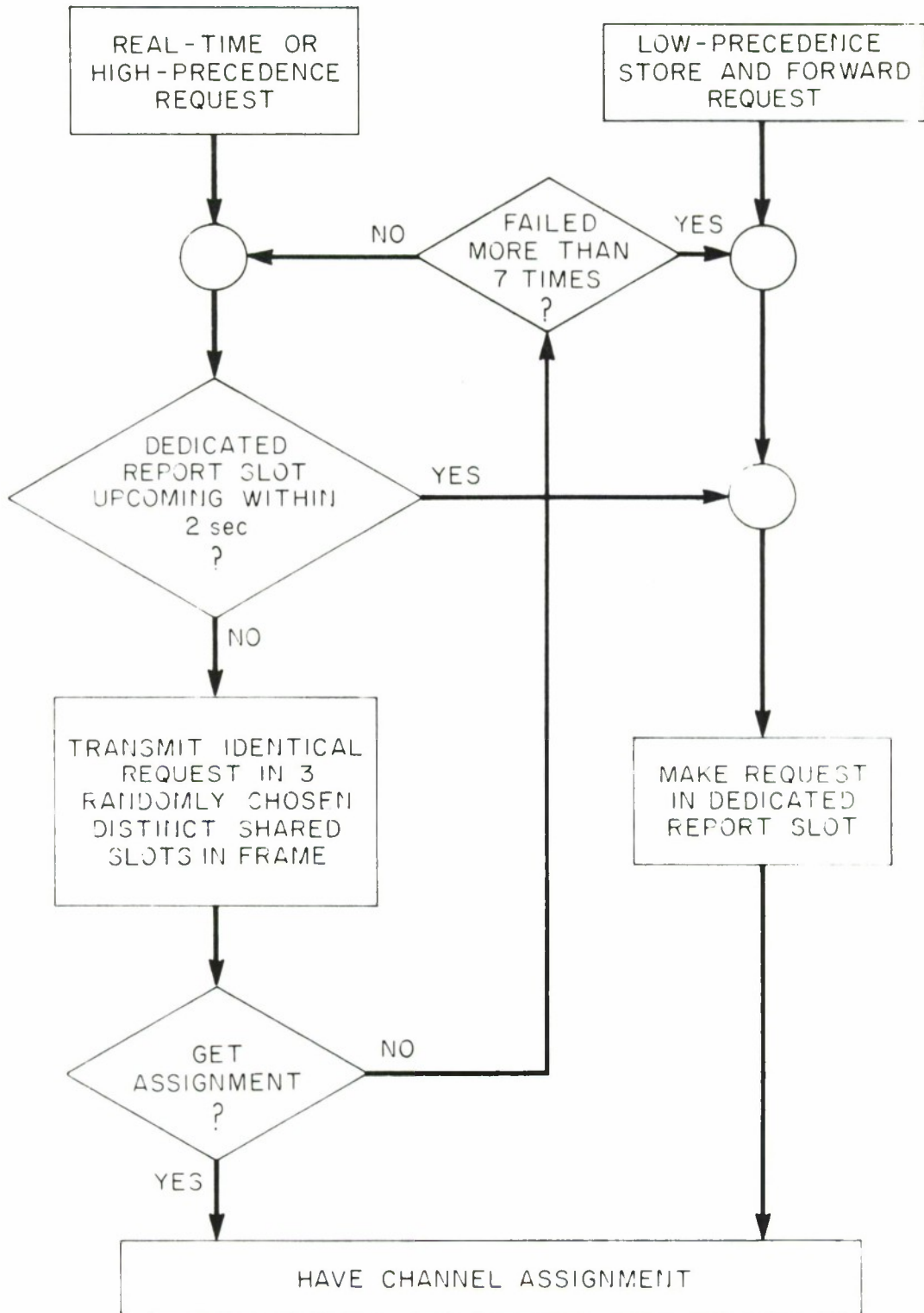
Fig. 3-8.   Flow chart of service request procedure for a ship.

The composite service request procedure for a ship is diagrammed in Fig. 3-8. The two main paths are for shared and dedicated slots. As indicated in the figure, the dedicated slot is used routinely for low precedence traffic. It is also used if it will occur within the next two frames or if there are more than, say, 7 conflicts (or incorrectly received controller responses) in the shared slots.

c. Aircraft/Submarine Signaling

Aircraft and submarines are expected to have calling statistics quite different from those of ships. Namely, both types of terminals will probably make infrequent requests for service, with submarines typically transmitting short messages and aircraft transmitting long messages. Under nominal conditions, with 10 aircraft and 40 submarines in a coverage area, the overall average request rate will be much less than one call per second, and therefore only a single shared slot per frame is provided. Because these terminals must signal at 1 Kbps, this request slot must be almost four times the duration of a ship request slot. Note that a ship could use the aircraft/submarine slot if it were operating in a degraded condition (e.g., with reduced transmitter power). The request algorithm would select at random one of three frames for transmitting a request, and in the event of conflict, a re-transmission would be made by again selecting one of the following three frames at random. In addition to the shared slot, one dedicated slot is provided in each frame in order to achieve a maximum response time of 50 seconds. Under heavy traffic conditions, with double the number of terminals, the single shared slot should still suffice, but two dedicated slots would be allocated in order to maintain the 50 second maximum response time.
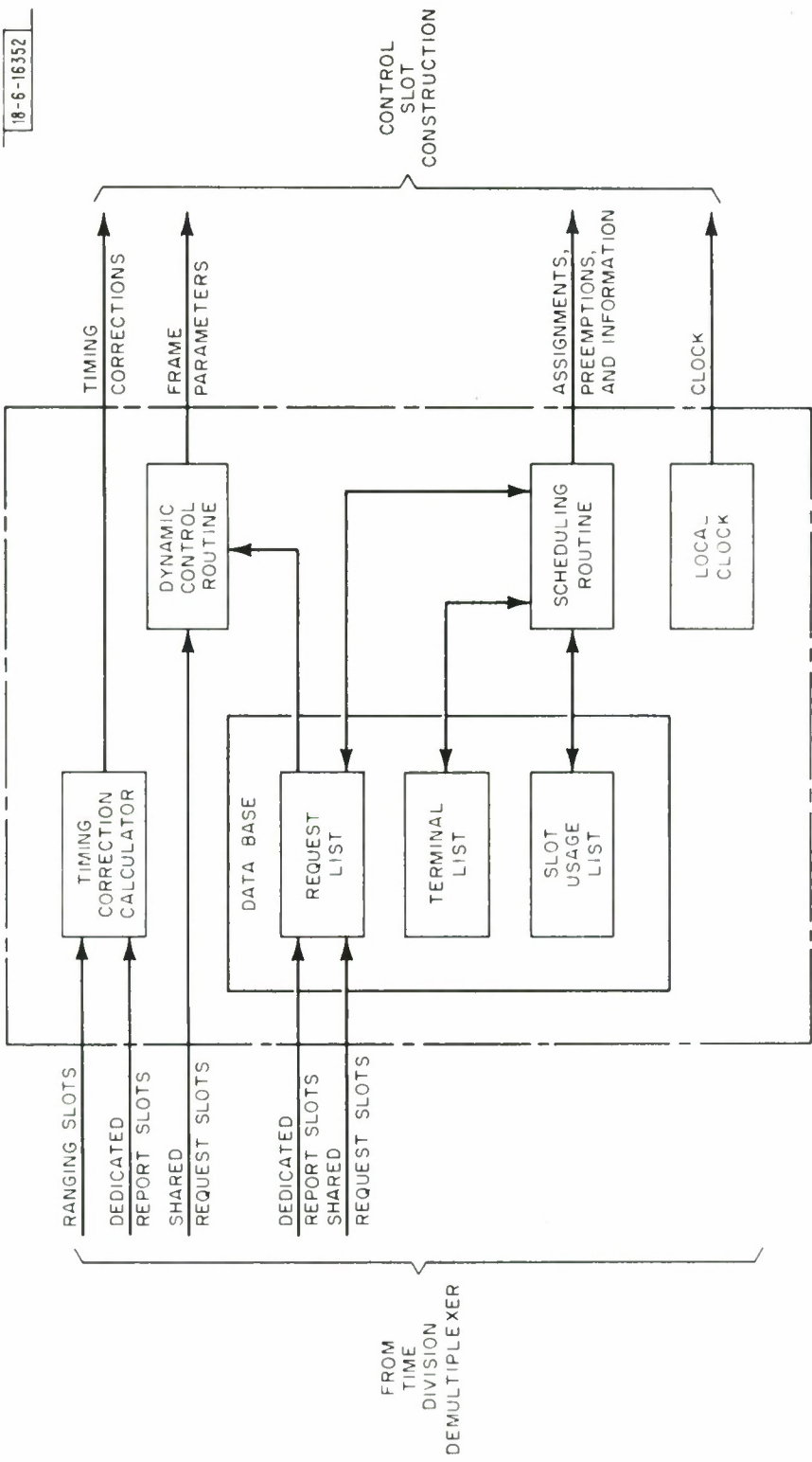
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Fig. 3-9.   Functional diagram illustrating controller operation.

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G.   Controller Operation

Figure 3-9 indicates schematically the essential functions of the central control station.   Section F on terminal operation covered some of these functions, so detailed descriptions are given here only on the data base, the scheduling routine, and the dynamic control procedures.   As explained earlier, the timing correction calculator monitors ranging slots and dedicated report slots, calculates the timing corrections, and transmits the corrections to the terminals in the upcoming control slot; the local standard is used to generate the system time-of-day clock and the framing sequence for each control slot.

Not shown in the figure is a function that may be included in order to inhibit traffic analysis by non-users of the system.   Such a function would locate idle slots by estimating the signal energy in every possible data slot.   This information would be used in conjunction with the data base to determine which of the presumably assigned slots had actually been relinquished. The controller would transmit dummy data in these slots as well as in unassigned slots.   In addition, free slots, recognized by the absence of signal power, would be returned to the pool of available slots.

1. Data Base

The controller data base contains all information necessary for the scheduling routine to assign and preempt data slots. The three lists which comprise the data base are the terminal list, the slot usage list, and the request list. The terminal list contains information on all user terminals that are allowed access to the system. Typical of this information are the following:

> terminal address
> terminal class
> number and type of transceivers
> current FLEETSAT usage
> net membership

The terminal address is simply the binary address of the terminal. Terminal class indicates the transmit and receive capabilities of the terminal, e.g., 'ship with one multicoupler'. A separate tabulation at the controller holds data on capability versus terminal class, equivalent to the data in Table 2-1. Each transceiver at a terminal is listed with respect to its status (active or inactive, and if in use, the location and precedence of each slot in use) and net membership.

The slot usage list contains the location, time of assignment, and precedence of each assigned slot, and the location of each available slot. Slot location includes the start and stop times of the slot within the frame, and the UHF channel which contains the slot.

The request list is simply a queue of all requests in order of time of arrival and precedence. When the scheduling routine makes an assignment, the request is removed from the list. When a preemption is made, the preempted circuit is placed at the top of the list for its precedence class.

As an example of the use of the data base by the scheduling routine, consider a request from one terminal for a circuit to another terminal. The scheduling routine then (1) validates the ability of the called terminal to receive the traffic, (2) calculates the link burst rate from data corresponding

to the two terminals (the burst rate is generally determined by the weaker
of the two communicating terminals), and (3) makes a slot assignment in keeping
with current slot usage of the called and calling terminals.

The principal advantage of maintaining a data base at a central location,
the controller, is the ease with which it can be updated. Additions or modifi-
cations to the data base would be necessary to accommodate such situations as
new or revised operational plans, changes in net membership, formation of new
nets, alteration of system capabilities, or motion of a terminal into or out
of a coverage area. Because of the possibility that the controller might fail,
the active controller must periodically broadcast to the standby controllers
any changes in the data base.

START

IS REQUEST LIST EMPTY ?

NO

YES

IS CALLED TERMINAL ACTIVE ?

NO

YES

DOES CALLED TERMINAL HAVE SLOT AVAILABLE ?

YES

IS SLOT AVAILABLE ON SLOT USAGE LIST ?

YES

NO

NO

DOES PRIORITY OF REQUEST EXCEED PRIORITY OF CALLED TERMINAL'S CURRENT CALL ?

NO

YES

DOES PRIORITY OF REQUEST EXCEED LOWEST PRIORITY ON SLOT USAGE LIST ?

NO

YES

UPDATE DATA BASE

UPDATE DATA BASE

UPDATE DATA BASE

CALLED TERMINAL INACTIVE

CALLED TERMINAL BUSY

INCOMING PREEMPTION

PREEMPTION

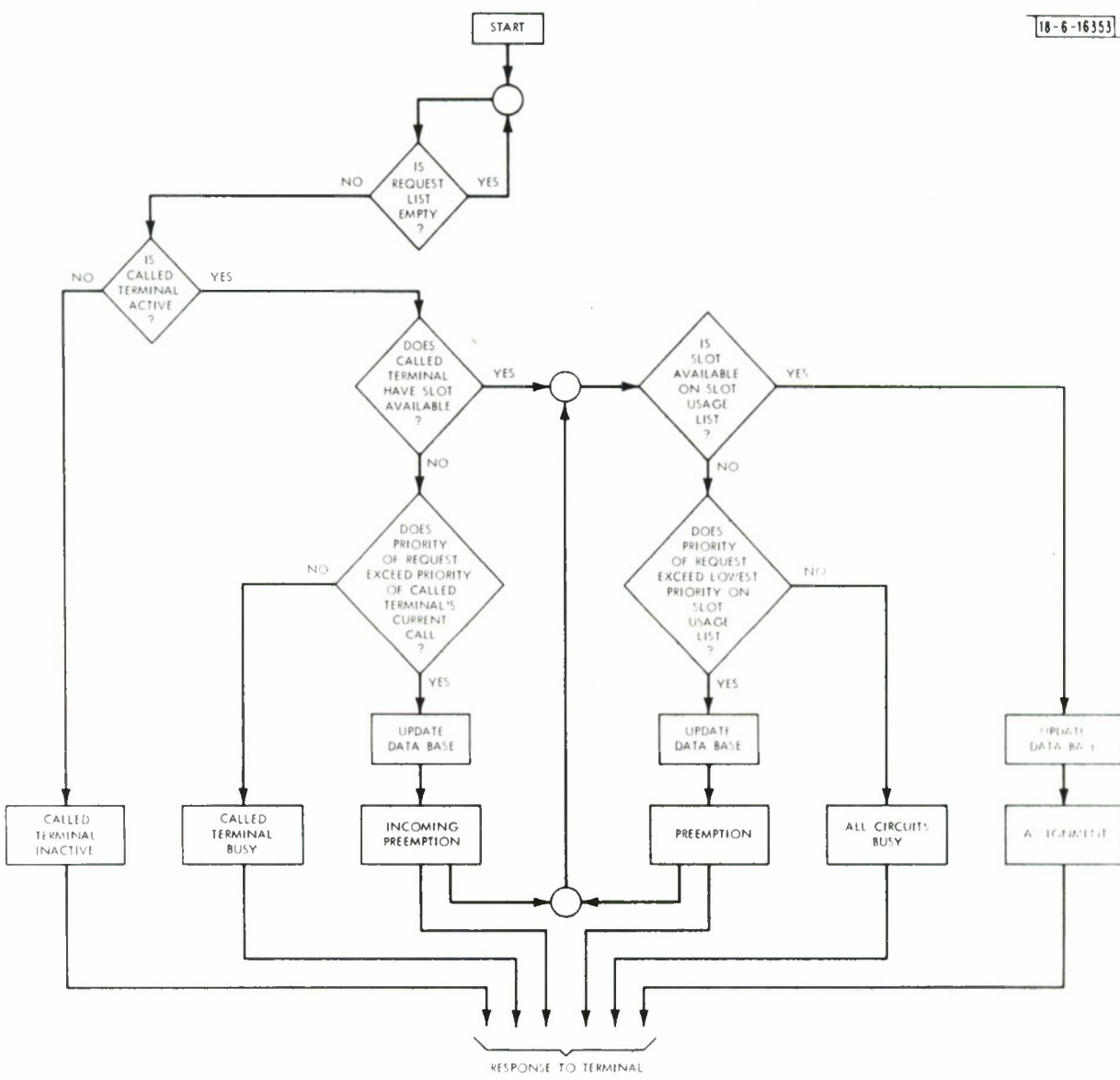ALL CIRCUITS BUSY

ASSIGNMENT

RESPONSE TO TERMINAL

Fig. 3-10. Flow chart of the scheduling routine.

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2.   Scheduling Routine

Figure 3-10 shows a flowchart of the scheduling routine. The objectives
of the routine are to act upon each new request, to provide the calling terminal
with a suitable response, to initiate preemptions when necessary, and to make
assignments for unserved requests as slots become available. Responses from
the controller to a user request include the following, as shown at the
bottom of the figure:

- called terminal busy
- called terminal inactive
- your circuit assignment is ...
- preemption in progress
- all circuits busy

A slot assignment is made by specifying the channel (4 bits for one of the
nine UHF channels), the millisecond within the frame at which the slot begins
(10 bits for 1-second frames), slot width (5 bits), the terminal address
(9 bits), and the message characteristics (7 bits), for a total of 35 bits.

In making slot assignments (and preemptions) the scheduling routine
must take into account the effective data rate, the link burst rate, and the
message and terminal type. The slot duration is calculated directly from
parameters in the controller data base. The location of the slot depends
upon the slot duration as well as upon constraints imposed by the terminals
that will communicate. Particular care is required in assignments to half
duplex terminals (or to full duplex terminals in a net with half duplex
terminals) and also to full duplex terminals that are already participating
in communications within other nets. The location of a slot in which a half
duplex terminal both transmits and receives is even more constrained than for
one-way traffic.

The scheduling routine searches the slot usage list for unassigned
slots with which to serve new requests. If no suitable slot is available,
then the scheduling routine searches the list for the last-assigned, lowest
precedence slot (1) that has sufficient duration to accommodate the new

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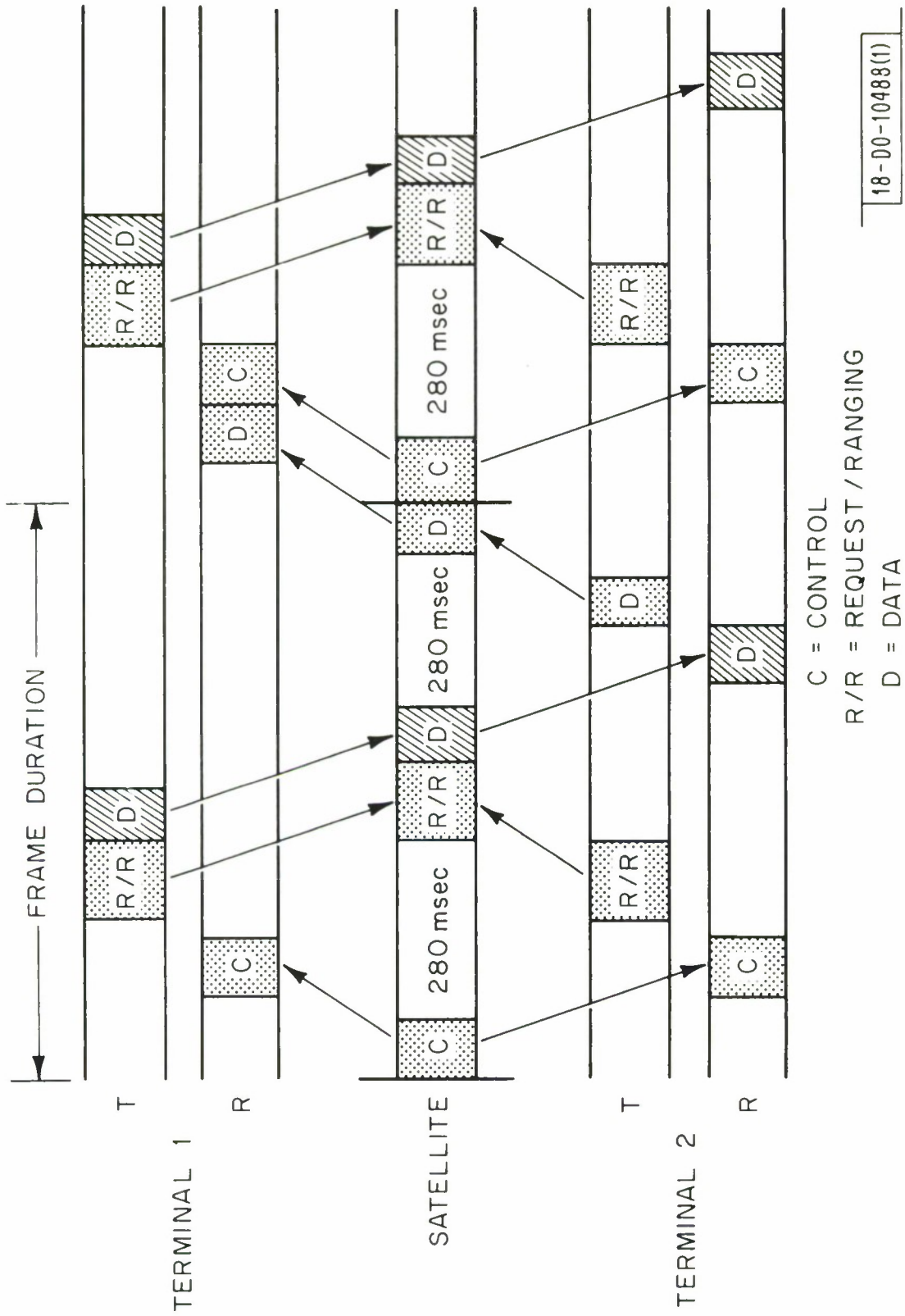
Fig. 3-11. Illustration of TDMA operation with a half duplex terminal participating in two two-way nets.

18-D0-10488(1)

request, (2) whose location within the frame can be utilized by the request, and (3) that is of lower precedence than the request. If such a slot (or combination of contiguous slots) is found, the controller assigns the slot to the new request and preempts the terminal currently using the slot. The scheduling routine can be structured to accommodate a variety of protocols for handling precedence. For example, it is possible to limit the precedence of certain users upon command from the controller. Moreover, the use of centralized control ensures that if conditions warrant, the precedence protocol can be readily modified.

As an example of how the proposed frame structure can accommodate half duplex terminals, Fig. 3-11 shows assignments made to two two-way nets with half duplex terminals. The central portion of the figure represents reference time at the satellite, and the upper and lower portions represent time at each of two terminals at maximum range from the satellite. For convenience, terminal time is split into transmit and receive times. The former leads satellite time by the one-way propagation delay (140 msec), and the latter lags by the same amount. Since a half duplex terminal can perform only one function at a time, transmit and receive slots must not overlap. Furthermore, since all terminals must monitor the control slot and must be capable of trans-mitting in a request slot, at the satellite these slots must be separated by at least 280 msec. To simplify terminal operation, the separation has been chosen equal to 280 msec, so that these slots are contiguous at a terminal on the edge of the coverage area. If the total duration of the control and the request/ranging slots is less than 280 msec, then it may be possible for half duplex terminals to utilize some of the 280 msec (as measured at the satellite) between the two slots. If, however, the total duration is greater than 280 msec, then none of this time can be utilized by half duplex terminals. As indicated in Fig. 3-11, in the present design the duration is indeed less than 280 msec, but it is close enough to that value that all of the 280 msec is assumed to be "restricted" in that it can be assigned only to full duplex terminals. On the other hand, slots following the request/ranging slot can

be assigned in an unrestricted fashion to a half duplex terminal. The figure shows two distinct data slots, indicated by different shadings, corresponding to two different assignments. So long as the separation between these slots is at least 280 msec (at the satellite), the transmit and receive functions will never overlap at either terminal, and at each terminal, traffic proceeds apparently simultaneously on two circuits.

3. Dynamic Control of Frame Parameters

Dynamic control of frame parameters has the effect of making the system responsiveness insensitive to relatively wide variations in the instantaneous traffic load or in other operating conditions. As one example, if the request rate increases (or decreases) sufficiently, the controller can increase (or decrease) the number of shared request slots. To perform this function, the controller monitors the number of requests and the number of conflicts in the shared request slots, and using information contained in the data base, estimates the actual request rate. If necessary, it then alters the frame configuration, transmitting information on the new frame parameters in the next control slot. A similar procedure could clearly be used to modify the ranging slot configuration. Whereas such procedures may not produce appreciably more communications capacity, they do more efficiently allocate portions of the capacity to control and to communications functions, maintaining a fairly uniform response time and ensuring prompt assignments to high precedence communications during heavy traffic. Further, such procedures are beneficial when request rates are low, because traffic flow need not necessarily be low, and the satellite system is then able to handle a large volume of low precedence store-and-forward traffic.

As a second example, consider the situation following a complete system outage, in which a large number of terminals may have a need to communicate but cannot do so until they all range. Many terminals attempting to range more or less simultaneously would hopelessly clog the shared ranging slot. However, since communications have presumably been interrupted by the outage, the controller can, for a brief period, devote a large fraction of the control channel to ranging rather than to communications. Thus, the controller can assign each terminal (or perhaps only those terminals that were active prior to the outage) a ranging slot. Using one channel, such a polled ranging procedure would require less than half a minute to handle all terminals in the coverage area.

4.   Handover of Control

In order to provide some degree of protection against the loss of the active controller, a number of standby controllers are equipped to assume the controller's duties. The difficult problems involved in achieving an orderly handover are for a standby to determine (1) that it is the controller that has failed (and not the satellite or the standby itself), (2) that the proper standby assumes control, and (3) that the standby is functioning properly. One procedure for handling controller handover is outlined below; no attempt is made to cover every possible alternative in this description, although the scheme is indeed self-consistent.

The controller transmits a framing sequence, or clock, on two distinct channels, one normally for ships, one for aircraft and submarines. The active and all standby controllers monitor both clocks. If only one of the clocks fails, the active controller switches the clock to another channel designated as an alternate for the clock (and all other control functions), and the standby controllers also switch to the alternate channel. Because of possible temporary channel degradations, a clock failure in the present context means the loss of the framing sequence over a number of consecutive frames. It is easy to see that the loss of a single clock can in all cases by resolved by switching channels, whether the loss occured because of failure at the controller, at the standby or at the satellite. For example, if after switch- ing to the alternate channel the controller still fails to receive its own clock, the controller ceases transmitting both clocks. The procedure for failure of both clocks is then followed. (Note that if there is a complete satellite failure, it does not matter what procedure is followed.) If the active controller observes failure in both clocks, it ceases transmission since such a failure mode will most likely occur because of a malfunction in its own equipment. Standby controllers are designated, in order of take-over precedence, c_1, c_2, c_3,.... After observing failure in both clocks, standby c_i waits iJ seconds and then sends a signal to itself in a special test slot provided in the request and ranging segment of the frame. (Although the controller is no longer transmitting, the time standards at the terminals-- especially at the standby controllers--are accurate enough to allow them to
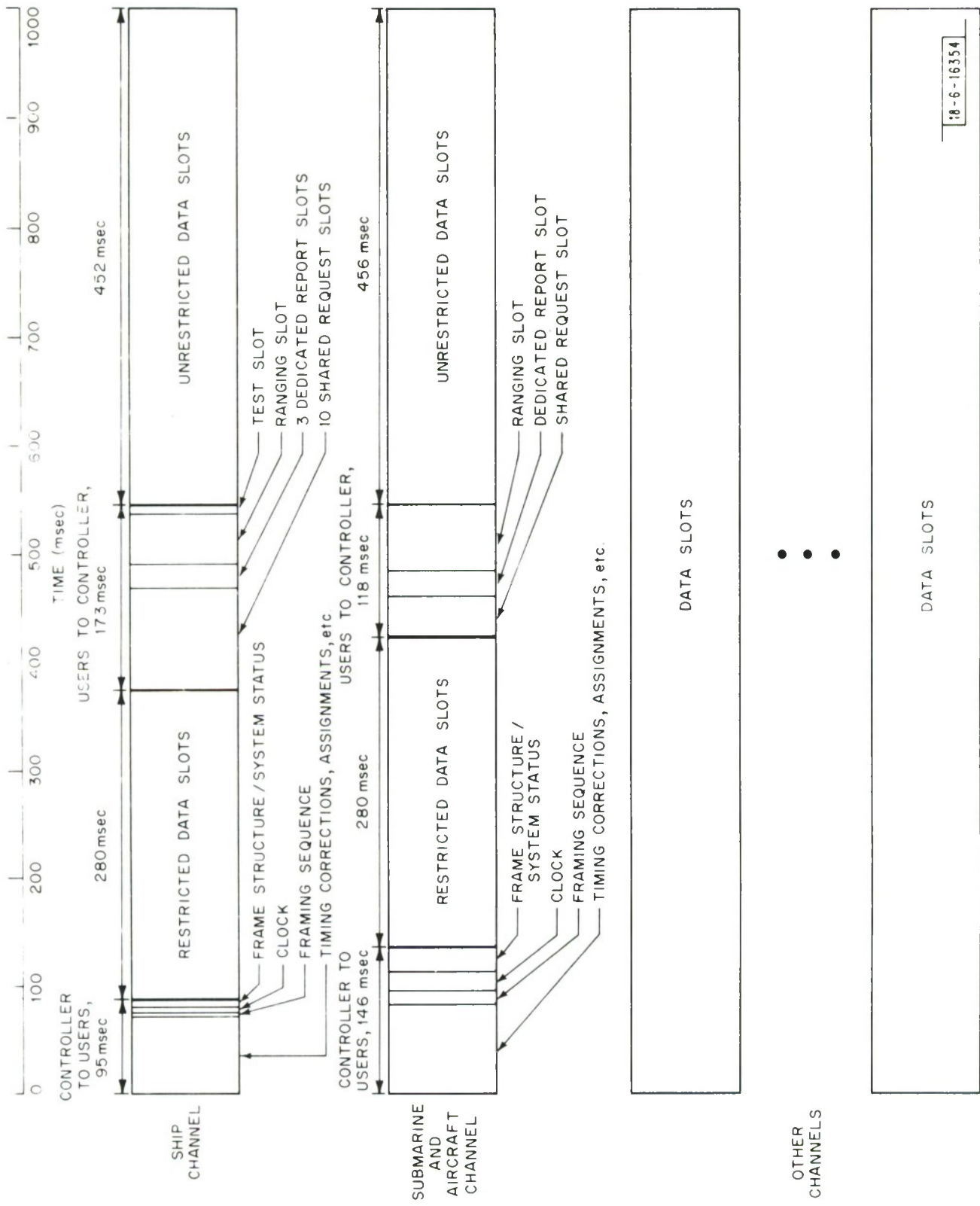
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maintain timing until they can assume control.) If the standby does not
properly receive its own test signal, it assumes that the fault lies in its
own equipment and does nothing further. If it does receive its test signal,
it begins transmitting both clocks, continuing to do so until the normal
controller issues a command to relinquish control.

In the above scheme, if a non-standby terminal--in particular one
that can listen to only one clock--fails to receive that clock, then it
too switches to the designated alternate clock channel. If it still fails
to receive the clock, then for some specified time it continues to search
for the clock on both the original and the alternate channels. Unless the
malfunction is in the terminal's own equipment or in the complete satellite,
the terminal will eventually hear a standby controller.

H.   Summary of TDMA Structure

The system described has a central controller which provides system timing and assigns slots, or circuits, on request from user terminals. Maximum demand assignment effectiveness results when slots are assigned from a large pool. Such a pool of slots is formed in this design from the portions of the nine UHF channels not permanently assigned or used for overhead. Assignment of slots is on the basis of first in, first out, by precedence. If all slots are assigned, a new request preempts the last assigned, lowest priority slot. To ensure preemptions and to maintain timing, each terminal monitors the control slot. Timely preemption is achieved by use of a one-second frame (which is also a compromise between the long frame time needed for greater efficiency and the short frame time desired for voice communications).

Most user terminals are ships which have a single half duplex transceiver. Such terminals, like all others, must monitor the control slot and transmit requests and periodic time tracking signals on the UHF channel that contains system control and signaling slots. They cannot, then, be assigned data slots on any channel in the initial portion of the frame ending with the request slots. Aircraft and submarines also have single half duplex transceiver, and therefore they too have this restriction on data slot assignments. System control and signaling for aircraft and submarines, however, take place at 1 Kbps, compared with 4 Kbps for ships. If all system control and signaling were placed on the same channel, the 1-Kbps transmissions to submarines and aircraft would unduly restrict the time available for assignments to ships. To avoid this problem, part of one channel carries a framing sequence, system control information, ranging, and signaling for ships, while part of another carries these data for aircraft and submarines. Finally, the transmission of two clocks is convenient in the handover of control from a failed active controller to a standby controller, as discussed in Section G-4.

Fig. 3-12. Detailed frame structure.

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Figure 3-12 shows the frame structure under nominal traffic conditions for each of the nine FLEETSAT-I channels. Tables 3-1 and 3-2 indicate the breakdown of the control slots and the signaling slots in the ship and in the aircraft/submarine control channels. The ship control slot is of sufficient duration to include one coarse timing correction (corresponding to the single ranging slot), three assignments with fine timing corrections (corresponding to the three dedicated report slots), and six assignments or preemptions (corresponding to the ten shared request slots). Note that in most cases the issuance of an assignment by the controller can be considered also to be implicitly a preemption if the assigned data slot is already in use. In addition to this information for specific terminals, 24 bits are set aside for messages of a broadcast nature, such as information on system status or frame structure. The control slot for aircraft and submarines allows space in consonance with the single shared request slot and the single dedicated report slot in that channel. Although the makeup of the control slots will of course vary substantially from frame to frame, the allowances in Table 3-1 were made to handle an expected worst case situation.

The data in Fig. 3-12 shows that for the nominal traffic conditions of 1.4 calls per second, ships require 27% of one channel for overhead (viz. control and signaling), while aircraft and submarines require 26% of another channel. This represents only 6% of the entire nine channels. All the other 94% is available for demand assignment as data slots.[*] The system therefore can provide a maximum of 109 data slots for 2.4 Kbps at a 32-Kbps burst rate (including 1 msec guard time for each data slot). This compares with the potential of 117 such circuits that could be derived in a dedicated format. The 8 circuits that are effectively used for overhead allow demand assignment, or sharing, of the satellite's capacity.

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[*] It should be noted that if fewer than nine channels are available, the overhead would exceed 6%. This is true since even though the number of request and assignment slots can be decreased consistent with the reduced traffic capacity, the framing sequence, clock, and ranging slot are of fixed duration.

TABLE 3-1

MESSAGES FROM CONTROLLER TO USER TERMINALS

	NUMBER OF BITS				SHIP CHANNEL		SUBMARINE & AIRCRAFT CHANNEL	
	Header (Message Type)	Terminal Address	Informa- tion	Total	Number of Each Message	Total Duration @ 4Kbps (msec)	Number of Each Message	Total Duration @ 1Kbps (msec)
Framing Sequence			14	14	1	3.5	1	14
Clock			17	17	1	4.3	1	17
Frame Structure/ System Status			24	24	1	6	1	24
Coarse Timing Correction	4	9	9	22	1	5.5	1	22
Fine Timing Correction	4	9	4	17	*		*	
Assignment and Fine Timing Correction	4	9	23	36	3	27.0	1	36
Assignment/Preemption	4	9	19	32	6	48.0	1	32
Other (e.g., Called Terminal Inactive or Busy, All Ckts Busy)	4	9		13	*		*	
					GUARD	1		1
					TOTAL	95		146

*

Not included because a worse case is assumed.

TABLE 3-2

USER TERMINAL TO CONTROLLER MESSAGES

	NUMBER OF BITS					SHIP CHANNELS		SUBMARINE & AIRCRAFT CHANNEL	
	Called Terminal & Net Address	Calling Terminal Address	Message Information	Total	Guard Time for Each Message (msec)	Number of Each Message	Total Duration @ 4Kbps (msec)	Number of Each Message	Total Duration @ 1 Kbps (msec)
Ranging		9	6	15	42	1	46	1	57
Shared Request	16	9	9	34	1	10	95	1	35
Dedicated Report (or Time Tracking)	16		9	25	1	3	22	1	26
Test		9	27	36	1	1	10		
						TOTAL	173		118

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Not all links, of course, can support 32-Kbps burst rates, and the maximum of 109 circuits diminishes as the number of users with link burst rates below 32 Kbps increases. For example, a 2.4-Kbps data slot for a submarine to COMMSTA link uses a burst rate of about 5.5 Kbps and so is six times as long as the basic 32-Kbps slot. Each such 2.4-Kbps submarine slot then subtracts 6 from the maximum. Similarly, each 2.4-Kbps slot for an aircraft (with a burst rate of 11 Kbps) subtracts 3 from the maximum. Demand assigned TDMA can thus handle a mixture of terminals, ranging from the most capable, which can operate at 32-Kbps burst rates, down to submarines, which can transmit at only 5.5-Kbps burst rates. The use of a flexible TDMA system therefore permits a tradeoff at any time between the total instantaneous throughput of the satellite and the number of disadvantaged terminals that are handled. Of course, if circumstances warrant, some channels can be assigned on a dedicated basis to particular users for some period of time.

In addition to efficiency in the use of UHF channels, the maximum utility of a given terminal's capabilities is also achieved by allowing, for example, multiple circuits between half duplex terminals. The efficiency in the use of UHF channels and of terminal capabilities is accompanied by rapid system responsiveness to user requests and by transparency of the system to the user; that is, the degree to which a circuit appears to a user to be a dedicated circuit. The 3-second access time surpasses the 10 second or greater time for a dialed circuit (on AUTOVON, say) and closely approaches the nearly instantaneous access time for a private line.

IV.   SYSTEM REALIZATION

Realization of the system operation described in Section III will require additional new equipment as well as changes to existing and planned equipment.   In this section, the physical realization of such new equipment is sketched and some suggested changes to existing equipment are briefly discussed.

A.   New Equipment

The TACM will make heavy use of programmable digital hardware in order to (1) obtain an efficiency and flexibility that results in improved system performance for a given cost, (2) achieve growth compatibility with FLEETSAT-I follow-on programs, and (3) minimize the need for periodic adjustment.   The modules which comprise the terminals include those needed for each transceiver, those for each terminal, and those for each principal or standby control station.   The per-channel modules are modulator/coder, demodulator/decoder, multiplexer, and demultiplexer.   Per-terminal modules are buffers, terminal signaling, and terminal controller.   In addition, each control station requires a system control module.
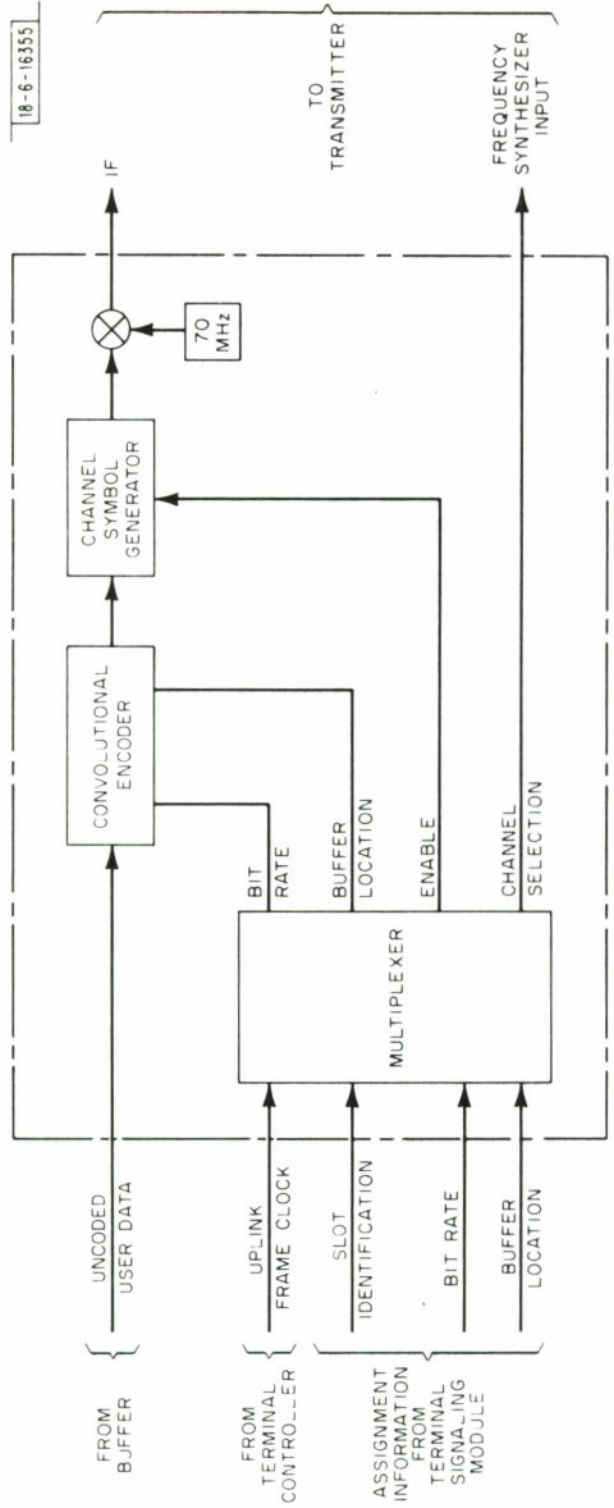
Fig. 4-1. Transmit chain of per-transceiver equipment.

1. Transmit Equipment

The modulator/coder and multiplexer modules are depicted in Fig. 4-1.
Except for some analog circuitry in the channel symbol generator, all
circuitry is digital, and none of the digital circuitry need be high speed
(the highest data rate envisioned is less than 50 Kbps). The channel symbol
generator will be all or part of a microprocessor. It might, for example,
be programmed for QPSK modulation for FLEETSAT-I, and for FSK modulation
for FLEETSAT-II. The equipment will include a 70-MHz oscillator to provide
the proper IF input to the transmitter. Control of the frequency synthesizer
for anti-jam modulation (frequency hopping) will also be included. The
encoder and multiplexer could be implemented completely with software. The
multiplexer receives assignment information from the terminal controller,
and from the terminal signaling module or system controller. This informa-
tion enables the multiplexer to control the encoder, modulator and transmitter.
The multiplexer supplies buffer location and bit information to the encoder.
The encoder then retrieves the data bit-by-bit from the buffer, encodes it,
and sends the coded quaternary input to the modulator. (For scintillation
coding, the data bits are interleaved.) The modulator, which is enabled by
the multiplexer for the duration of the data slot, then transforms the
quaternary digital input to QPSK baseband, for input to the transmitter.
The multiplexer also selects the proper channel with a command to the trans-
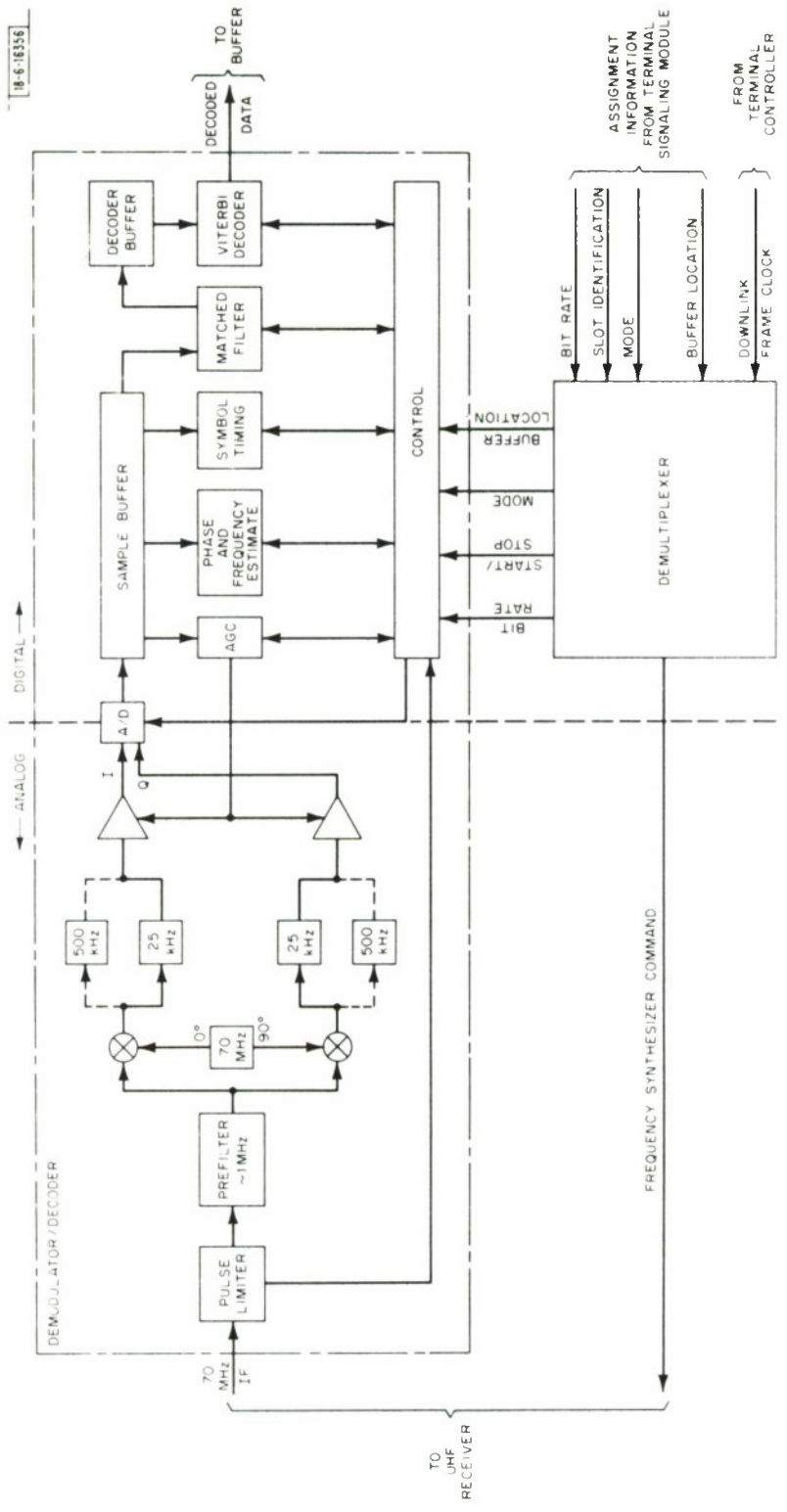mitter frequency synthesizer.

Fig. 4-2. Receive chain of per-transceiver equipment.

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2. Receive Equipment

Figure 4-2 shows the receive chain, namely the demodulator/decoder and demultiplexer modules. The 70-MHz IF output of the UHF receiver is pulse limited to remove much of the energy of signals affected by pulse RFI, pre-filtered, and mixed down to in phase and quadrature baseband components. Note that the 70-MHz local oscillator, although stabilized with respect to the terminal frequency standard, is not part of a phase locked loop. The baseband signals are then filtered by a baseband filter ∿25 KHz wide for FLEETSAT-I. A second, wider filter could be provided as a strapping option; in this way upgrading to FLEETSAT-II would involve only software modifications.* The filtered analog baseband signals are then amplified and digitized. The final selection of sampling rate and A/D quantization levels requires some simulation and analysis, but in this preliminary design we assume 4-bit quantization and sampling at the Nyquist rate.

Up to the analog/digital interface, the signal processing is relatively standard, save for the free-running local oscillator and the lack of an analog AGC loop. Beyond that interface, the demodulator implementation is more novel. The digitized samples are first shifted into a register called a sample buffer. The remainder of the signal processing is accomplished by a number of sub-programs operating on the buffer samples under control of a master program contained in a microprocessor. Thus, the AGC program determines the analog gain by estimating the averaged received energy in a block of samples. An appropriate signal is then fed back to the amplifiers

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* The wider filter may, in fact, be some sort of matched filter that in effect carries out some analog pre-processing.

in both the I and Q channels. With the limited dynamic range of 4-bit quantization, setting the analog gain properly is very important. Additional RFI pulse blanking can be performed at this point. In a similar manner, symbol timing, phase, and frequency (including Doppler shift) are estimated on a block of samples in the buffer, and as with the AGC, the estimates are periodically updated to maintain the necessary accuracy. By arguments similar to those used in Sec. III-F on ranging requirements, it is possible to show that data bursts have sufficient energy to enable these estimates to be obtained rapidly without a preamble. Using the time, phase and frequency estimates, the in-phase and quadrature samples are combined and passed to the matched filter, which produces quantized (soft decision) symbols for the decoder. Also input to the decoder control may be information from the analog pulse limiter and the digital pulse blanker (if any) specifying which symbols should be classed as erasures.

One of the important advantages of the digital implementation outlined above is that the receiver functions operate effectively in parallel on samples that are held (and modified) in a relatively large buffer. Performance is therefore superior to that of analog equipment in which the corresponding functions must typically be carried out sequentially. The digital implementation is expected to be simpler, less expensive, and more accurate, but it also has the advantage that it can be readily adapted, under program control, to varying burst rates, data rates, and even code structures. Moreover, no preamble is required because the data from a burst are retained in the buffer; preamble-free acquisition is more efficient in general, but is particularly efficient in a TDMA system in which short bursts are possible. Another advantage of a microprogrammed implementation arises because in the FLEETSAT-I TDMA system, communicating terminals do not maintain phase, frequency, or even timing accuracy between bursts. Therefore, although some bursts may be short enough to require only one estimate of a parameter, each parameter must be acquired on each new burst. However, a repeat estimation within a burst is in principle no different

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from the initial estimation, and with microprogramming the same estimation algorithm (i.e., the same hardware and software) can be applied both to the initial acquisition of the burst and to updates during the burst.

Since it is desirable to implement only one type of modem, the basic design must be capable of handling the maximum traffic load, which for FLEETSAT-I is thirteen separate 2.4-Kbps circuits, each at a burst rate of 32 Kbps. Preliminary calculations indicate that apart from the decoder, parallel processing would not be required. That is, the speed of present-day TTL logic should enable all the receiver functions, excluding the decoder, to be implemented with a single microprocessor and with serial operations.* A separate microprocessor would perform the Viterbi decoding. Implementation of such a decoder for operation at 32 Kbps should not be difficult since relatively inexpensive commercial models exist for considerably higher data rates. Total storage requirements for the sample buffer and the decoder buffer should be less than 50 Kbits.

The demultiplexer performs functions similar to the multiplexer, and in addition provides a mode control indication to the control program. The two modes are "normal" and "initial acquisition". In the normal mode the operation is as discussed above. In the initial acquisition mode, no start and stop pulses are given. Rather, the demodulator looks for the framing sequence at a specified data rate on a specified channel.

B. Modifications to Existing Equipment

In order to realize an efficient TDMA system for FLEETSAT, changes to existing equipment should accompany new equipment. In some cases it is necessary to actually replace existing equipment. FLEETSAT-I is fundamentally

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* FLEETSAT-II might use a much higher downlink data rate (e.g., 500 Kbps), but the data would be in one continuous stream, thereby simplifying the processing chores. Thus, the number and type of computations would be significantly reduced (e.g., burst acquisition is no longer performed on each data burst of interest) and with some analog pre-processing, the number of samples per symbol could be decreased, so that the same digital hardware should be capable of handling the higher rate data.

an FDMA satellite. The earth terminals designed for use with FLEETSAT-I
and earlier systems is also FDMA in nature. Therefore some shortcomings
might be expected in using such terminal equipment in a TDMA mode. Such
shortcomings, as discussed in Section II, include long transmit-to-receive
turnaround time of the transceiver, and the switching time of the electro-
mechanical T-R switch in a submarine installation. In addition to problems
associated with use for TDMA, some of the equipment has drawbacks for FDMA
applications. (Since the pool of demand assigned slots are time division
multiplexed in each of nine UHF channels, the design described here is in
reality a hybrid TDMA-FDMA system.) One example of such a drawback is the
long (50 msec.) settling time of the ARC-156 transceiver frequency synthesizer.
However, a remedy for this drawback would be expensive and is not essential
since the ARC-156 is used in aircraft, which are only a minor portion of the
communications load on FLEETSAT-I.

Other deficiencies, however, involve equipment of ship terminals, whose
communications are the majority of the FLEETSAT-I load. Correction of such
deficiencies would lead to more effective satellite utilization and to increased
reliability of operation. Implementation of the WSC-3 modifications that would
decrease the turnaround and settling times (cf. Table 2-1) are relatively in-
expensive and would enhance system throughput significantly. Modifications to
the WSC-5, on the other hand, are probably not necessary since COMMSTAs--the
only WSC-5 users--should be equipped with full duplex terminals on each channel.
Finally, on a submarine, replacement of the present electromagnetic switch
with a solid state transmit/receive switch would lead to improved reliability
and performance. In addition to incorporating those modifications which are
more or less straightforward, some effort could be devoted to realizing a
more efficient substitute for the multicoupler, and to obtaining an elevation
stabilized mount for the OE-82 antenna. Both of these items would increase
system capabilities, the multicoupler perhaps being more important.

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A time division multiplexing scheme is described for use with FLEETSAT. Available communications circuits would be shared among a much larger pool of users by demand assignment, with a central controller allocating satellite resources. The system achieves rapid circuit assignments and preemptions with relatively high efficiency.

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