FILE COPY

ESD-TR-75-96

MTR-3041

ESD ACCESSION LIST
DRI Call No. 83533
Copy No. 1 of 2 cys.

THE "STANDARD" MUX BUS: SOME CONSTRAINTS ON INFORMATION FLOW ARISING FROM MIL-STD-1553 (USAF)

NOVEMBER 1975

Prepared for

DEPUTY FOR DEVELOPMENT PLANS
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
Hanscom Air Force Base, Bedford, Massachusetts

Approved for public release;
distribution unlimited.

Project No. 6370
Prepared by
THE MITRE CORPORATION
Bedford, Massachusetts
Contract No. F19628-75-C-0001

ADA017677

When U.S. Government drawings, specifications, or other data are used for any purpose other than a definitely related government procurement operation, the government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise, as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Do not return this copy. Retain or destroy.

REVIEW AND APPROVAL

This technical report has been reviewed and is approved for publication.

EMERY F. BOOSE
Project Leader
MITRE D-92

KEITH HANDSAKER
Project Engineer

FOR THE COMMANDER

JOHN B. TINDALL, Lt Col, USAF
Acting Director, Technological Planning
Deputy for Development Plans

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Date Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ESD-TR-75-96	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* THE "STANDARD" MUX BUS: SOME CONSTRAINTS ON INFORMATION FLOW ARISING FROM MIL-STD-1553 (USAF)		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER MTR-3041
7. AUTHOR(s) P. R. Cloud		8. CONTRACT OR GRANT NUMBER(s) F19628-75-C-0001
9. PERFORMING ORGANIZATION NAME AND ADDRESS The MITRE Corporation Box 208 Bedford, MA 01730		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project No. 6370
11. CONTROLLING OFFICE NAME AND ADDRESS Deputy for Development Plans Electronic Systems Division, AFSC Hanscom Air Force Base, Bedford, MA 01731		12. REPORT DATE NOVEMBER 1975 13. NUMBER OF PAGES 43
14. MONITORING AGENCY NAME & ADDRESS*(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* UNCLASSIFIED 15e. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

STANDARD MUX BUS
MIL-STD-1553

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

MITRE has designed, constructed, and operated an avionics time division multiplex bus compatible with the requirements of MIL-STD-1553 (USAF). In the course of engineering the software to perform the message control function for this network, some constraints on the message flow were encountered that are not immediately apparent when reading the standard. The purpose of this report is to alert the

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Date Entered)*

20. ABSTRACT (concluded)

system designer to some of these potential difficulties. Four main topics are discussed:

- Bus capacity
- A time constraint on message handling
- Subaddresses, and Data Word accessibility
- Temporal characteristics of information transferred on the bus

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS AND TABLES

1.0 INTRODUCTION

MITRE is currently supporting the Electronic System Division of the Air Force in the area of digital avionics. One aspect of this work has been a continuing critical evaluation of MIL-STD-1553 (USAF), a document that has recently been issued to standardize the characteristics of time division multiplex data buses for use in aircraft. Much of the earlier comment on this standard was qualitative in nature and based primarily on heuristic considerations. However, sufficient progress has now been made, both in physically implementing a "standard" bus, see Figure 1, and in the performance of supplementary calculations, to warrant a somewhat more detailed and quantitative evaluation of some of its requirements. The topics covered in this report fall, loosely, within the area of information flow over an avionics bus network, and have been selected because they obtruded into the design of MITRE's experimental system. For the latter, it was acceptable to make arbitrary decisions so that the work could proceed at a rapid pace. However, when finalizing a standard for an operational system, a more systematic approach is necessary, since the ramifications of any decision may be very significant. This report contains a brief account of some problems that were encountered, and that deserve further attention by the designer of a "standard" bus network.

The material is treated under three main headings. Background, covered in Section 2.0, abstracts pertinent portions of MIL-STD-1553 (USAF), and where appropriate, discusses them in relation to the MUX bus network.

Section 3.0, Specific Constraints, contains the main content of the report. It examines some elementary data handling constraints that are implicit in the standard or arise from its ambiguities and omissions. The particular topics covered are:

- Bus capacity, Section 3.1
- A time constraint on message handling, Section 3.2
- Subaddresses and Data Word accessibility, Section 3.3
- Temporal aspects of signal information transfer by an avionics bus, Section 3.4.

Section 4.0, Summary and Conclusions, briefly summarizes the content of the report, and indicates the potential problem that is presented in the quest for the "standard" bus.

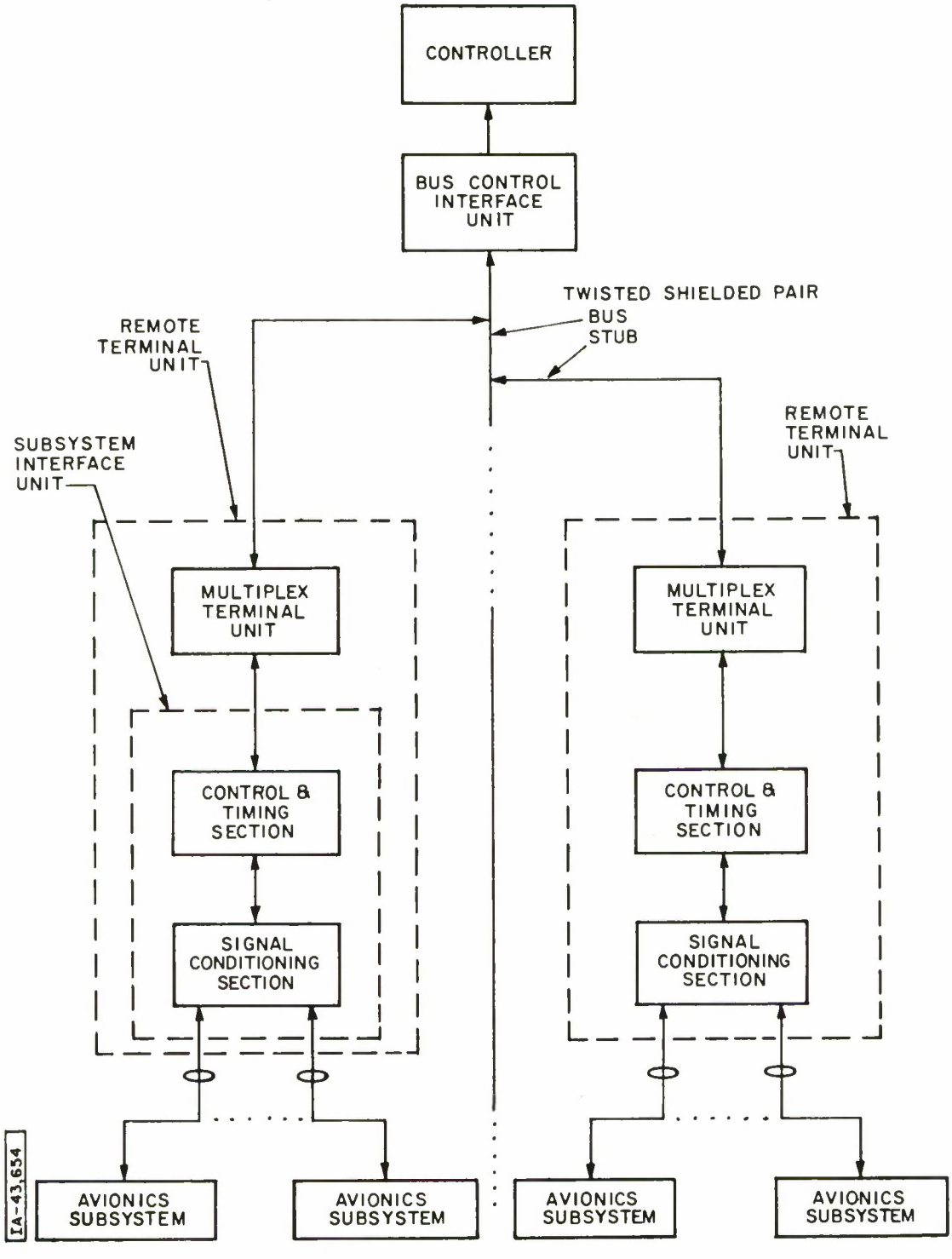


Figure 1 A "STANDARD" MULTIPLEX BUS
MIL-STD.-1553 (USAF)

2.0 BACKGROUND

A number of factors referred to in the following sections, and used in the calculations, are contained explicitly and/or implicitly in MIL-STD-1553 (USAF). For convenience, the pertinent paragraphs are abstracted below with explanatory notes where this is considered desirable.

2.1 Data Rate and Bus Capacity

Section 4.2.3.3 of MIL-STD-1553 (USAF), 30 August 1973, states, "Data Rate. The data transmission rate on the bus shall be 1.0 megabit per second with..."

This is an explicit statement concerning the rate at which the bits within a message are placed on the line, and when considered in conjunction with other sections of the standard, leaves no doubt as to the intent of the requirement.

The absence of any explicit mention of bus capacity in the standard, either in Section 3.0 on definitions or in Section 4.0 giving requirements, necessitates some measure of interpretation. It should perhaps be stated at the outset of the following discussion that this author thought the intent of the standard was quite clear! However, any ambiguity in this area could result in serious incompatibilities, both within and between bus systems; thus the subject warrants further discussion. The point of contention is whether the standard implicitly places a requirement on the bus capacity, or if this parameter is left under the control of the bus designer.

When binary waveforms are used on a line, it is fairly common usage, although perhaps incorrectly so, to identify the data rate of the transmission with the capacity of the line. Thus in the present case, the requirement that the bus should operate at a data rate of 1 megabit per second implies that the system should be capable of placing one million bits on the line each second. Thus, a "standard" bus system would have the capability of operating at a duty cycle of 100 percent. Whether any particular application of the multiplex bus on board an aircraft requires operation at a high duty cycle is a different, but relevant, question. This point was discussed with the authors' of the standard when it was originally issued, and there was general agreement on the above interpretation. Indeed any different understanding leads rapidly to a number of conclusions that run contrary to the basic tenets of standardization, and would negate many of the very real advantages to be gained by establishing identity of critical bus parameters.

While the arguments in favor of specifying a capacity for the bus system are conclusive, the question of what that value should be is somewhat contentious. Since the standard was originally issued, considerable work has been done on various aspects of its implementation, and some of the implications of attempting to operate a bus at a high duty cycle, using the message formats defined in the standard, have been examined. Some quantitative results arising from various combinations of these conditions are given in Section 3.2.

Before leaving this topic, one other point should be discussed. Several mission oriented studies have been made to determine the information flow on the bus arising from servicing various avionics suites, and the resulting data processing load for the message handling function. Their results have been construed to indicate that the bus will be so under utilized that the questions of whether or not the bus can be operated at a high duty cycle, and whether it is used efficiently, are academic and not worth consideration. As to the first point, the question of a high duty cycle arises from the implicit requirement of the present standard. Perhaps the figure is impracticably large, but the crucial factor is that some definite requirement for the "standard" bus must be given; it is necessary to avoid incompatibilities when integrating bus subsystems into a bus network, and when interfacing different "standard" buses with one another. As to the other point of operating a bus efficiently--in the context of information transfer--there are various design constraints that significantly reduce the capacity of the line available for signal transfer between units, which are not immediately apparent to a system designer reading the standard, and warrant further consideration before reckless use is made of this resource.

2.2 Word Characteristics

Sections 4.2.3.4 and 4.2.3.5 of MIL-STD-1553 (USAF), 30 August 1973, define the word characteristics--size and format--that can be used on the bus. The contents of these sections are summarized diagrammatically in Figure 2.

2.3 Message Formats

Section 4.2.3.6 of the standard describes the bus protocol that will be used on the line; the content is summarized in Figure 3.

It is the message and word formats, shown in Figures 2 and 3, which determine the "overhead" that is incurred with each transfer of information on the line. Consequently, they establish an upper bound on the fraction of the nominal capacity of the bus (1 Mbps), that is available for the interchange of signals between source/sink

IA-43,656

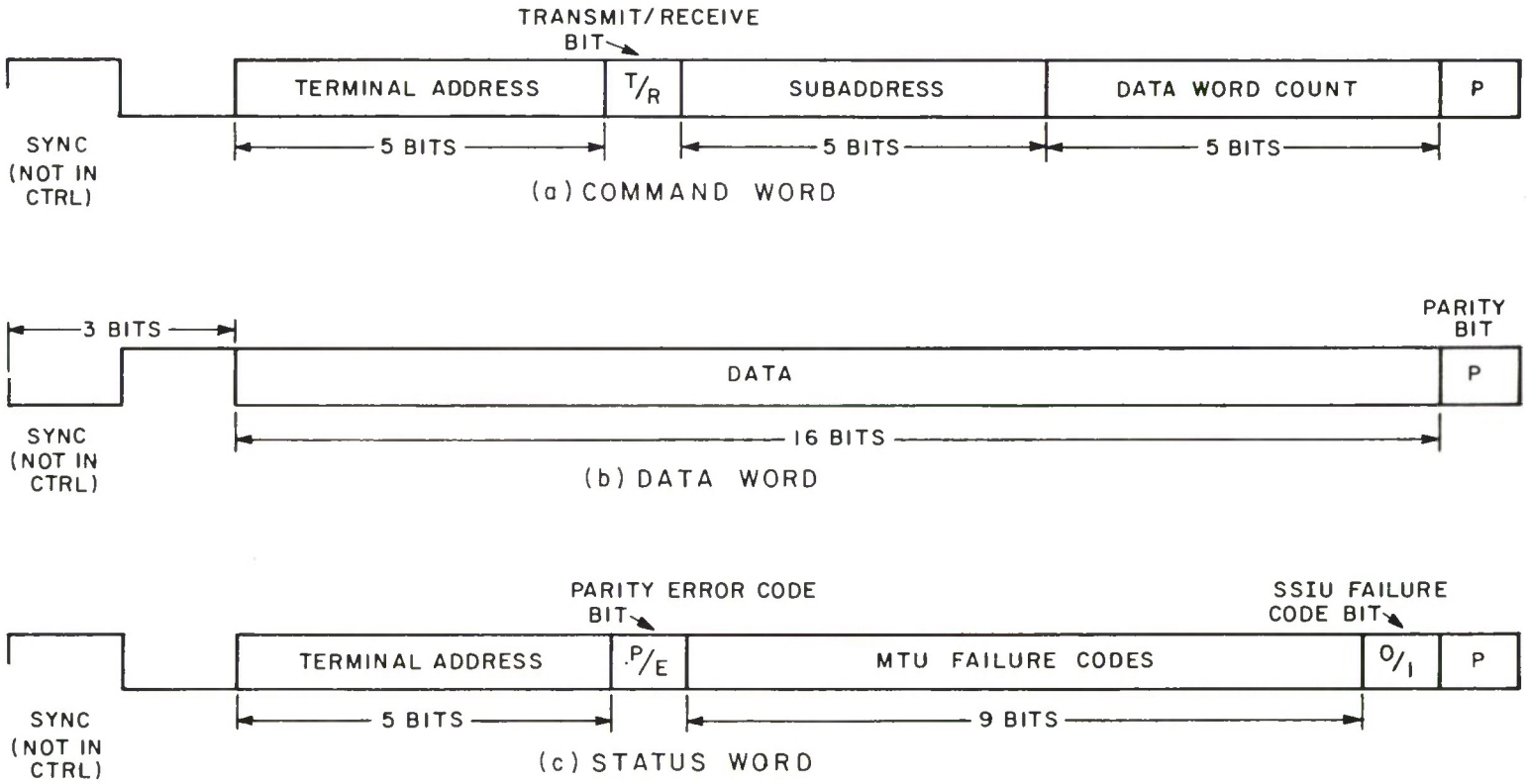
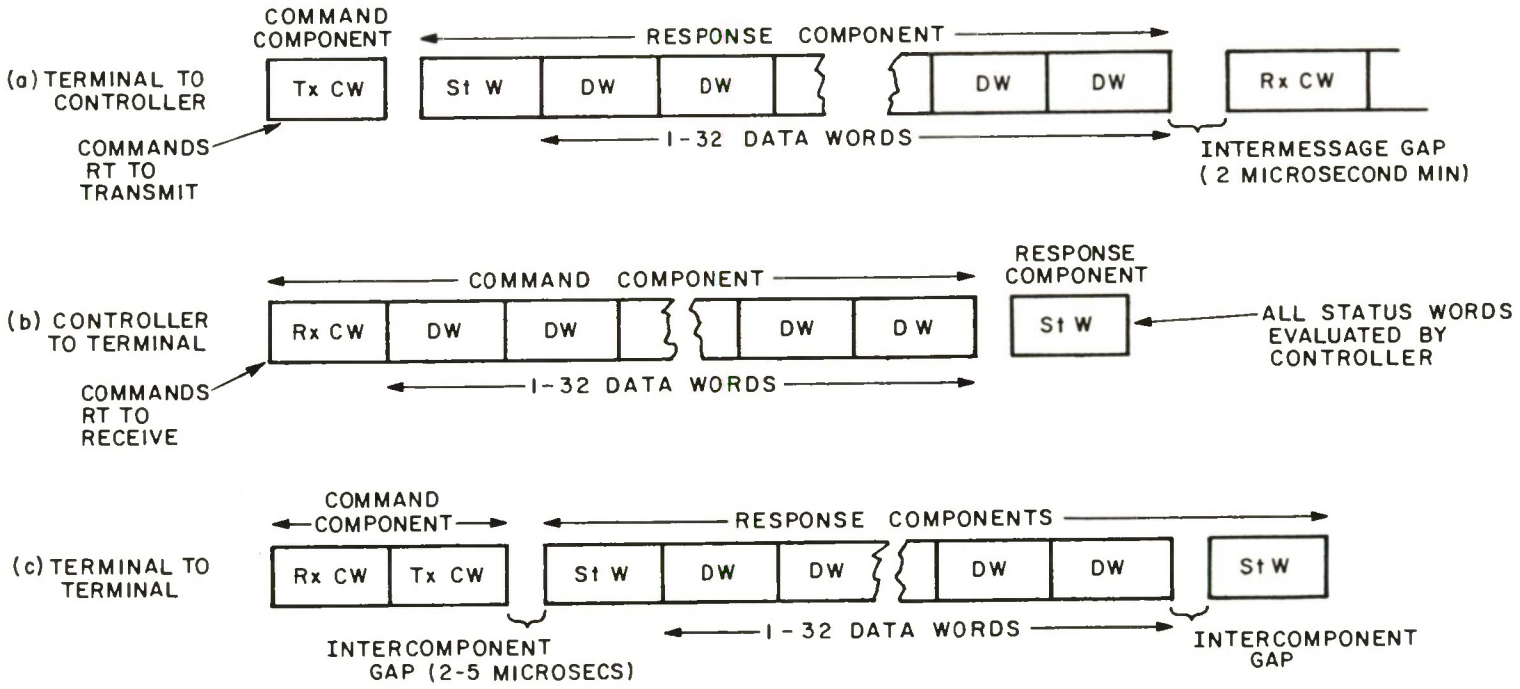


Figure 2 WORD FORMATS
MIL-STD-1553 (USAF)

IA-43,655



(1) COMMAND COMPONENT: SEQUENCE OF CONTIGUOUS WORDS TRANFERRED FROM CONTROLLER TO REMOTE TERMINAL.

(2) RESPONSE COMPONENT: SEQUENCE OF CONTIGUOUS WOROS TRANSFERRED FROM RT TO CTRL OR RT TO RT.

Figure 3. MESSAGE FORMATS ON MULTIPLEX BUS

pairs serviced by the line. These constraints on the information capacity of the bus are discussed in Section 3.1.

2.4 Suitability of Subsystem Signals to Bus Transfer

Section 10.3 in the appendix to MIL-STD-1553 (USAF) briefly discusses the suitability of various classes of signals to transfer on the bus. The section is reproduced in its entirety below.

> "10.3 Multiplex selection criteria. The selection of candidate signals for multiplexing is a function of the particular application involved, and criteria will in general vary from system to system. Obviously those signals which have bandwidths of 400 Hz or less are prime candidates for inclusion on the bus. It is also obvious that video, audio, and high speed parallel digital signals should be excluded. The area of questionable application is usually between 400 Hz and 3 KHz bandwidth. The transfer of these signals on the data bus will depend heavily upon the loading of the bus in a particular application. The decision must be based on projected future bus needs as well as the current loading. Another class of signals which in general are not suitable to multiplexing are those which can be typified by a low rate (over a mission) but possessing a high priority or urgency. Examples of such signals might be nuclear event detector output or a missile launch alarm from a warning receiver. Such signals are usually better left hardwired, but they may be accommodated by the multiplex system if a direct connection to the bus controller's interrupt hardware is used to trigger a software action in response to the signal."

The guidance given to the system designer on this topic is so general that bus systems developed by different organizations--in consonance with the standard--could well be incompatible as to the classes of information they could handle. There is no doubt that the task of standardizing the signal classes, in regard to suitability for bus transfer, would be substantial; however, unless more definitive criteria are given, and the range of uncontrolled variability reduced, inter-bus compatibility will not be ensured. Further discussion of this topic is given in Section 3.4.

3.0 SOME SPECIFIC CONSTRAINTS ON INFORMATION FLOW

Prior to the generation of MIL-STD-1553 (USAF), which governs the standardization of avionics TDM data buses, there was no guidance as to a preferred network configuration, operational concept, or message format. As a consequence, different data buses intended for use in the same vehicle were not readily able to communicate with one another. The issuance of MIL-STD-1553 (USAF) was a major step towards avoiding such problems in the future, and is certain to contribute significantly towards the goal of compatibility. However, the development of an all encompassing standard for a system as complex as an avionics bus network is a virtual impossibility, and it can only be hoped that any shortcomings that exist are relatively inconsequential. In the year fiscal 75 MITRE has used the standard as the basis for the design of an experimental bus, thus there has been need to examine its contents in some detail. In configuring the message control processing, various questions arose concerning the information flow on the bus, and unambiguous answers could not be found in the standard. The uncertainties that remained, and some consequences that derived therefrom, would permit the development of incompatible "standard" buses, and thus seemed worthy of further consideration by the network designer. Four of these areas are discussed below:

- Bus capacity, Section 3.1
- A time constraint on message handling, Section 3.2
- Subaddresses and Data Word accessibility, Section 3.3
- Temporal aspects of signal information transfer by an avionics bus, Section 3.4.

3.1 Bus Capacity

Following the discussion of Section 2.1, it will be assumed that the intent of MIL-STD-1553 (USAF) is that the avionics TDM bus, with its associated remote terminal units, should have a nominal capacity of 1 Megabit, i.e. be capable of operating at a data rate of 1 Mbps at a 100 percent duty cycle. While this requirement is, in itself, of some significance, a more useful parameter for the system designer--particularly since the line must operate with the prescribed protocol--is the capacity in terms of signal information bits.

It is convenient for the present purpose to consider the overall system capacity of 1 Mbps as consisting of two classes of information. One of these is the "applications", or signal, information which it is the function of the bus network to transfer

between the various source/sink pairs. The other is the "overhead" information, which is used to effect the "applications" information transfer, and is a by-product of the line protocol defined in the MUX bus standard. Since all signal information transfer of necessity incurs the transfer of overhead information, the capacity of the bus in terms of the former is less than 1 Mbps, and in some circumstances very significantly so.

When operating the avionics bus according to the prescribed discipline, the fractional percentage of the overall data transferred that falls within the category of overhead is a strong function of the message lengths employed. For example, if a command/response sequence executes a single Data Word (DW) transfer from a remote terminal (RT) to the controller (CTRL), the message sequence consists of a Command Word (CW) from CTRL to RT, a 2-5 microsecond interval, followed by a Status Word (SW), a contiguous DW containing 16 information bits from RT to CTRL, and a 2-5 microsecond gap; resulting in a fractional overhead of 3/4 (~75%). Alternatively, if the requirement was to transfer 32 Data Words, the Status Word would be followed by 32 contiguous DW, yielding an overhead ratio of 25%. Extrapolating these considerations to an operational system, the fractional "applications" capacity available to the system designer will be a function of the message sequence mix necessary to effect the necessary signal information transfers. Further, as the message mix is changed in response to mission contingencies, so will the available applications capacity. A quantitative investigation of these factors is better left until the conditions are further constrained, and a practical message mix formulated. However, an estimate of the decrease in capacity due to overhead can be obtained from computations based on a less complex model:

(a) Bus is loaded--including inter-message and component gaps--at 1 Mbps.

(b) All message sequences are of same type, e.g. all remote terminal to controller, etc.

(c) All messages contain same number of Data Words.

Using these simplifications, curves of available capacity versus number of Data Words/message have been generated, with message type, and intercomponent/message gap, as parameters, see Figure 4. A sample calculation is given in Appendix 1.

It should be noted that the "available capacity" represented in Figure 4 is the maximum bus capacity available for the transfer of signal information between source/sink pairs. Further constraints which will not, in general, permit this capacity to be achieved in

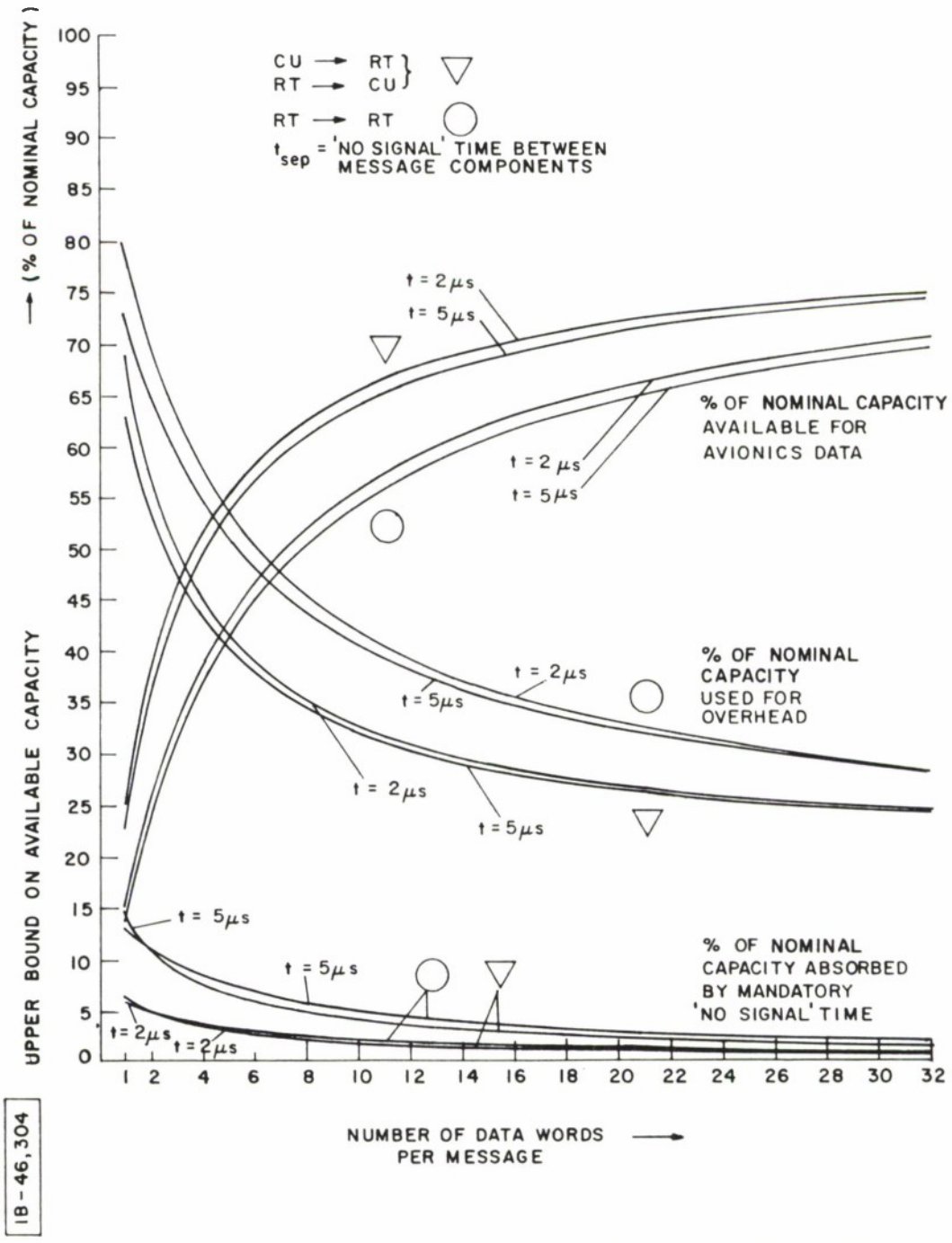


Figure 4 "STANDARD" MUX BUS : UPPER BOUND ON PERCENTAGE OF NOMINAL CAPACITY AVAILABLE FOR AVIONICS SIGNALS

practice, arise from the details of the interchange of signal information between the user equipments that the bus is required to service. In the example given above it was tacitly assumed that a Data Word contained 16 bits of signal information to be transferred from source to sink. However, it is quite probable that the number of signal bits to be transferred between any given pair of bus users cannot readily be subdivided into sixteen bit blocks, thus requiring some additional overhead bits be appended to complete the partially filled DWs. The one Data Word transfer of the previous example which gave an available signal capacity of 25 percent is an extreme case. If the only signal information to be transferred in this message was a discrete--a switch position, say--then fifteen bits of the sixteen in the DW would be classed as overhead and the fractional signal capacity would decrease to ~2 percent. (Alternatively, the fractional overhead capacity would increase to ~98 percent.) If an estimate is made of the average fractional utilization of a Data Word, i.e. (average number of signal bits per DW)/ 16), the effects of this partial DW usage can be obtained from its fractional value multiplied by the fractional available signal capacity shown in Figure 4.

The foregoing is a relatively simplistic assessment of the influence of the line discipline, defined in MIL-STD-1553 (USAF), on the signal capacity--in contrast to the nominal capacity--of the TDM bus. The problem will be touched upon again when the topic of word and message packing is discussed in Section 3.2.1.

3.2 A Time Constraint on Message Handling

It has already been pointed out in Section 2.0, that the USAF goal of developing a "standard" avionics bus according to the requirements of MIL-STD-1553 (USAF) implies that the bus components be capable of operating at a 100 percent duty cycle, even if a particular application does not make these demands. With this fact in mind, some calculations were made to determine the time available for the basic control operations necessary to fulfill the primary bus functions of collection, transfer and distribution of data between source/sink pairs, while the system is under maximum load, i.e. operating at 100 percent duty cycle.

It should be noted that for the present purpose the control function has been narrowly defined. In essence the network is being treated as a transfer device, with attention being confined to moving the data between source/sink pairs without consideration as to its content and any prior or subsequent processing that this might require. It is further assumed that "no error" conditions exist; the purpose being to avoid--in this report--the complexities of network reconfiguration and similar types of operation, which would certainly fall within the scope of any but the most

restrictive of definitions of the bus control function. The primary reasons for adopting this definition of bus control are twofold; first, it has been the aim to obtain an appreciation for the problem based on relatively elementary calculations; second, the "peripheral" control activities, e.g. network reconfiguration, status monitoring, etc., are not treated in MIL-STD-1553 (USAF), and thus their scope, and method of implementation, are more under the control of the system designer than are the mandatory capabilities defined in the standard.

The timing constraint considered in this section is that arising from the message handling capability of the bus system. This parameter is a derivative of the data rate on the line, the bus discipline and bus capacity; all of which are explicitly or implicitly contained in the standard. In the present case each of the requirements, when treated separately, appears to be relatively innocuous; however, when considered together, the resulting requirement on the message handling capacity is quite severe. For example, the data rate on the line is to be at 1 Mbps: this is performance well within the present state-of-the-art, the passenger service system on the Boeing 747--which uses a TDM bus--operates at a data rate of 6 Mbps.

The bus discipline described in the standard permits a range of message structures. These are shown diagrammatically in Figure 3, and their respective durations in time are given in Table I. The latter conversion was made via the data rate, word lengths in bits, synchronization and intermessage/component gap characteristics, all contained in the standard. Coupling the requirement for operation at 100 percent duty cycle with the message durations given in Table I, the curves of Figure 5 were generated, showing the variables (number of messages per second) versus (number of Data Words per message), with message type and "gap" times as parameters. It can be seen that the message handling capacity--at a 100 percent duty cycle--spans a range of approximately 1.5K to 15.5K messages per second, dependent upon the number of Data Words in each message.

TABLE I

Duration in Time of Bus Message Modes

Message Mode	#Data Words	#Overhead Words	Intercomponent Gap	Intermessage Gap	Minimum Duration (micro-secs)
Remote (Min) Terminal	1	2	1	1	64
to (Max) Controller	32	2	1	1	690
Controller to (Min)	1	2	1	1	64
Remote (Max) Terminal	32	2	2	1	690
Remote (Min) Terminal to	1	4	2	1	106
Remote (Max) Terminal	32	4	2	1	735

Some consideration of the control function in the context of the data processing demands imposed on the controller will indicate that the message is the basic processing unit. The message rate and capacity, coupled with the data processing requirements per message, are of more significance to the controller than the line data rate. The bus activities associated with each message unit are the fundamental steps of collection, transfer and distribution of data, and when the system is operating at 100 percent duty cycle, the processing in the controller arising from each of these operations must be performed, effectively, in real time. If the maximum message handling capacity is considered, i.e. one Data Word transfers between RT and CTRL, Table I indicates that the available time for processing the message is approximately 64 microseconds; alternatively, the minimum handling capacity, i.e. 32 DW transfers, permits an interval of 690 microseconds. Which of these is the more restrictive will depend on how the processing varies with message length. For example, each additional DW in a message has a 20 microsecond duration on the bus, and thus provides an increase of that amount for message handling. If the additional processing time incurred by the extra DW is less than 20 microseconds, there will be a net gain; if the incremental processing time per word is greater than 20 microseconds, there will be a net loss. Since the

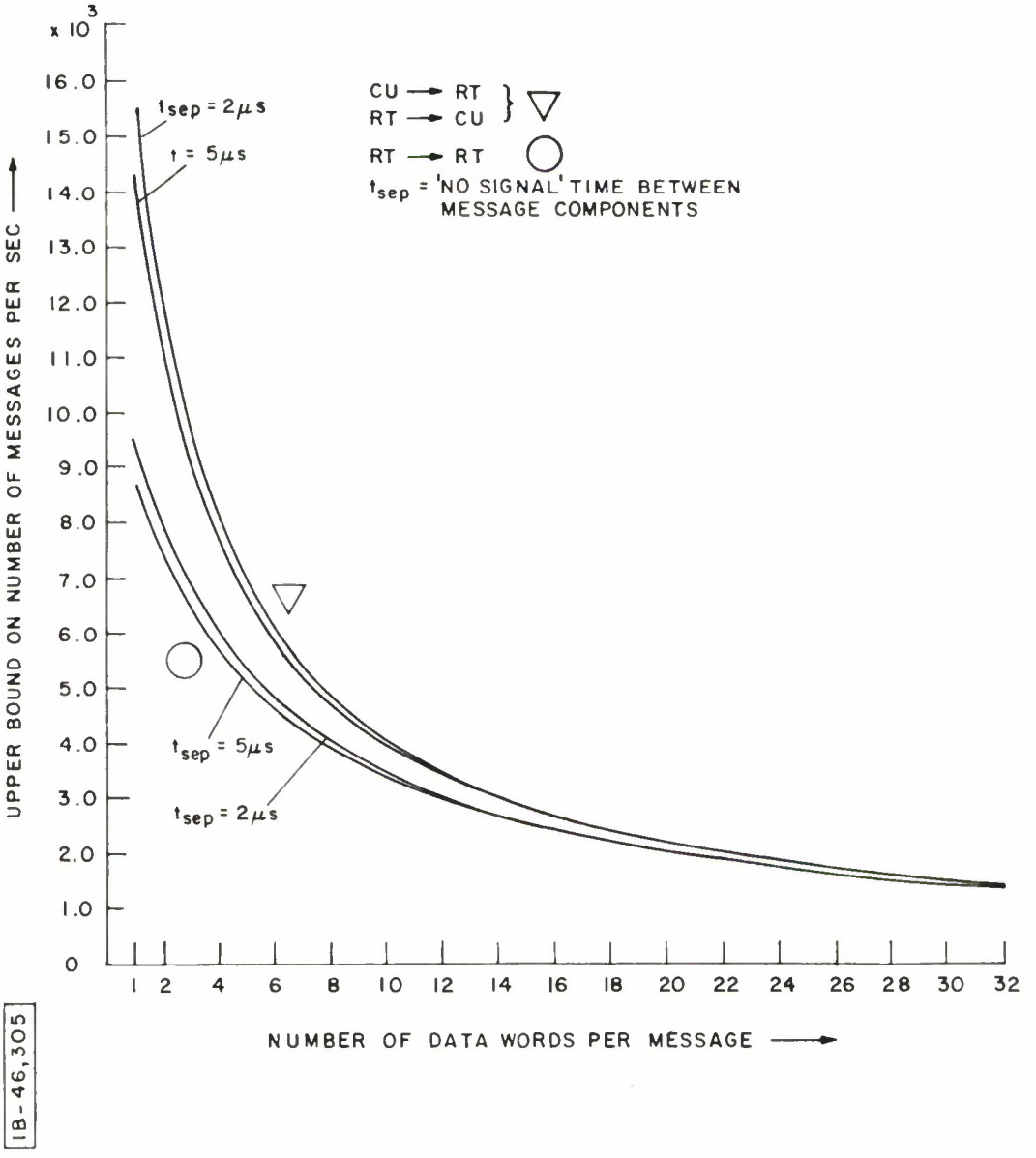


Figure 5. UPPER BOUND ON NUMBER OF MESSAGE SEQUENCES PER SECOND

resolution of this point involves more detailed investigation than is warranted in this report, attention will be confined to a one DW command/response message sequence and its associated available processing time of 64 microseconds. In terms of a typical general purpose digital computer (GPDC), that might be used as a bus controller, this interval is equivalent to about 35 instructions of the mix used in message handling.

To obtain an estimate for the number of instructions that might be required if the control processing was to be done by a GPDC, advantage was taken of the work that is currently being done at MITRE on the implementation of a rudimentary bus system in accordance with MIL-STD-1553 (USAF). The bus control aspects of this work have been outlined in two previous reports, References 2 and 3, and will not be discussed further herein. The estimate of time and number of instructions for a single DW message sequence given in Figure 6 was obtained from Reference 2. The numbers indicate clearly that the view originally put forward that the basic bus control function could be absorbed by a GPDC as a negligible extension to its other functions is not tenable when considered in the context of a "standard" bus which must have the capability of operating at 100 percent duty cycle. It is these considerations that have initiated the design of a more sophisticated hardwired unit to interface the GPDC to the bus; its purpose will be to absorb the majority of the routine control functions shown in Figure 6, and thus reduce the load on the processor.

The time constraint outlined above becomes apparent even when the scope of the control function is confined to its bare essentials. Any broadening of its scope to include other control activities--particularly if necessitating additional processing in the GPDC on each message sequence, can only compound the problem. The timing constraint will be touched upon again when the topic of word and message packing is discussed in the next section.

3.2.1 The Packing of Multiple Signals Into a Data Word

One aspect of the message handling software that merits particular attention is that of distributing the signals contained in the received Data Words to the appropriate applications routines within the bus controller. In its simplest form this might be thought of as placing an incoming Data Word into a predetermined location in core so that it can be accessed by the user function as required. Analysis of various equipments has shown that many signals transferred between source-sink pairs serviced by the bus can be represented by small bit fields, and the dedication of a separate Data Word--which potentially has 16 information bits--to each signal would significantly reduce the effective information

IA-43,657

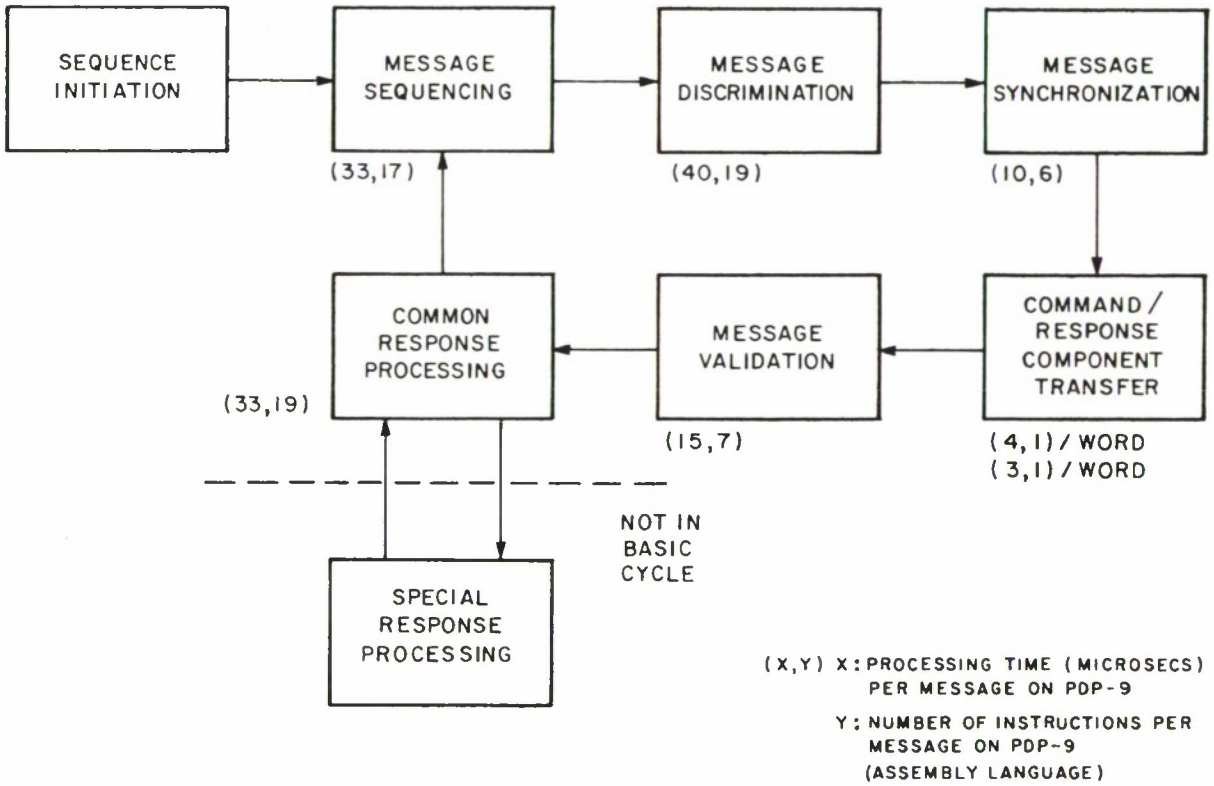


Figure 6 EXPERIMENTAL BUS CONTROL SOFTWARE : BASIC CYCLE

capacity of the system. To avoid this loss of capacity, it has been suggested that several signals be packed into a single Data Word. Thus, the information density of the word would be increased, and the capacity of the bus be more efficiently utilized. However, in the context of the message handling software, a distinction must be made between the case of n bits of a Data Word representing a single signal and being processed as an entity by a single applications routine, and that of the n bits being comprised of several signals each destined for a separate applications routine. The difference lies in the magnitude of the unpacking and internal distribution task. To clarify the point, consider a specific example as it might apply to the experimental TDM bus. Data words from the remote terminals are transferred from the bus--a shielded twisted pair--to the core of the bus controller--a PDP-9 general purpose digital computer--via the bus control interface unit. All received Data Words in an incoming message are stored in a common buffer in core. Each word is then distributed to the location appropriate for access by its application routine. The PDP-9 is a single address machine, with a memory cycle of one microsecond, and without general purpose registers. The transfer of a Data Word containing a signal from the common buffer to the user location consists of a two instruction load and store sequence requiring four memory cycles. If the Data Word contained four signals each required by a different user routine, then four three-instruction sequences--load, mask, and store--would be required to distribute the information, using 24 memory cycles in all. This six-fold increase in time taken by the internal distribution of the information arises from a relatively conservative example of packing. If 16 discretes were packed into a Data Word, the increase would be 24 times. Moreover, in some instances, e.g. if the packed signals were represented by two bit binary numbers, further operations would be necessary to present the correct magnitudes to the applications routines.

This example illustrates that while the technique of word packing increases the information density within a Data Word, there is an accompanying increase in the time required per Data Word, and hence per message, to unpack and distribute the information to the user routines within the bus controller. Comparison of the time requirements for these operations with the execution times of the other components of the basic message cycle indicates that the unpacking and distribution of the signals within the bus controller has the potential of being the most time consuming phase of the message handling activities.

Although not explicitly mentioned previously, it will be apparent that there are analogous considerations in regard to execution time involved in the collection and packing of signals into the Data Words within the bus controller, prior to transferring them to a remote terminal. These steps will not be reviewed in

detail; however, it should be noted that they constitute an additional significant contribution to the execution time of the basic message handling cycle.

Another consideration related to word packing and unpacking within the bus controller is the requirement that such an approach imposes upon the remote terminal. This technique presupposes a level of sophistication in the processing capability of the remote terminal sufficient to perform corresponding packing and unpacking activities. The time constraints are not as restrictive as those at the bus controller, and for this reason a microprocessor has been suggested for the task. If the capability of present day microprocessors to meet these requirements is questioned, the argument is frequently advanced that the bus controller is required to perform the message control operations associated with servicing 32 remote terminals, whereas the microprocessor is dedicated to a single terminal. The implication is that although present microprocessors are slower than conventional computers, the differential is not so great as to warrant the question! While the description of the relative functions of the bus controller and the remote terminal processor is accurate, it should be recalled that there is no requirement in MIL-STD-1553 (USAF) that the bus network should always have a large number of terminals, nor that they be serviced in order. If a multiplex bus is servicing many terminals, it is quite likely that a given remote terminal would be required to participate in several successive bus controller/subsystem information transfers. Although a microprocessor might be quite adequate to meet the average processing load, its ability to cope with the fluctuating demand is not so apparent. It is possible that some of these difficulties could be met by careful scheduling of the microprocessors tasks. However, the necessity for such sophistication in the programming of the remote terminals is most undesirable.

3.3 Subaddresses and Data Word Accessibility

It has been pointed out in Section 3.1 that the available capacity of a "standard" bus for the transfer of user data between equipments being serviced is significantly less than might be supposed by the use of a 1 Mbps rate on the line, see Figure 4. However, these curves represent upper bounds on the available information capacity which cannot readily be attained in an operational system. Many factors can lead to this shortfall. A quantitative evaluation of their absolute, and relative, significance would be sufficiently complex--in execution rather than concept--to necessitate a simulation involving alternative bus architectures, suites of avionics equipments, and a range of aircraft missions. Such an effort does not fall within the scope of MITRE's present work in the area of avionics buses. However, an

heuristic discussion of some of the factors arising from various constraints in MIL-STD-1553 (USAF) which may lead to a de facto reduction is in order.

3.3.1 Addressing Memory at Remote Terminals

A conceptual representation of the distributed memory, i.e. the storage located at the remote terminals, associated with a "standard" bus and the address fields for referencing it, are shown in Figures 7 and 8.

The first subdivision--to the level of a remote terminal--is referenced by a five-bit field termed the MTU address. Its magnitude provides for a potential loading of 32 uniquely addressable remote terminals per bus system.

The second subdivision is addressed by a single bit field--the transmit/receive bit. According to MIL-STD-1553 (USAF), the intent is to indicate the action required of the remote terminal (RT). However, it can also implicitly reference two distinct areas of the memory within the RT; one dedicated to the storage of incoming information--when the RT is in receive mode; the other confined to the buffering of the outgoing data--when the RT is in the transmit mode.

The third level of addressing consists of a five-bit group, the subaddress/mode field. For the purposes of the present discussion, the only significance of the mode designation is to eliminate one address (00000) of the 32 possible subaddresses, each of which defines a unique block of storage within the remote terminal.

The fourth subdivision is at the level of a word block within a subaddress, and is referenced by a five-bit word count field. Thus, the maximum number of storage locations associated with each subaddress--T/R bit--pair is 32.

In total then, there is a maximum of 1984, (2 x 31 x 32), Data Word locations at each remote terminal. One half--predetermined--of these is available for words received from the bus controller or other remote terminals, and the remaining half is for words transmitted to those units. However, due to the nature of the word count parameter, the words at any subaddress are not, in general, separately accessible. The standard does not define a method of identifying the required word within a block, so for convenience of discussion the convention shown in Figure 7 is adopted; it consists of consecutively numbering the storage locations from one end. Then if the bus controller requires the rth DW at a given subaddress, it will issue a command word to the appropriate remote terminal

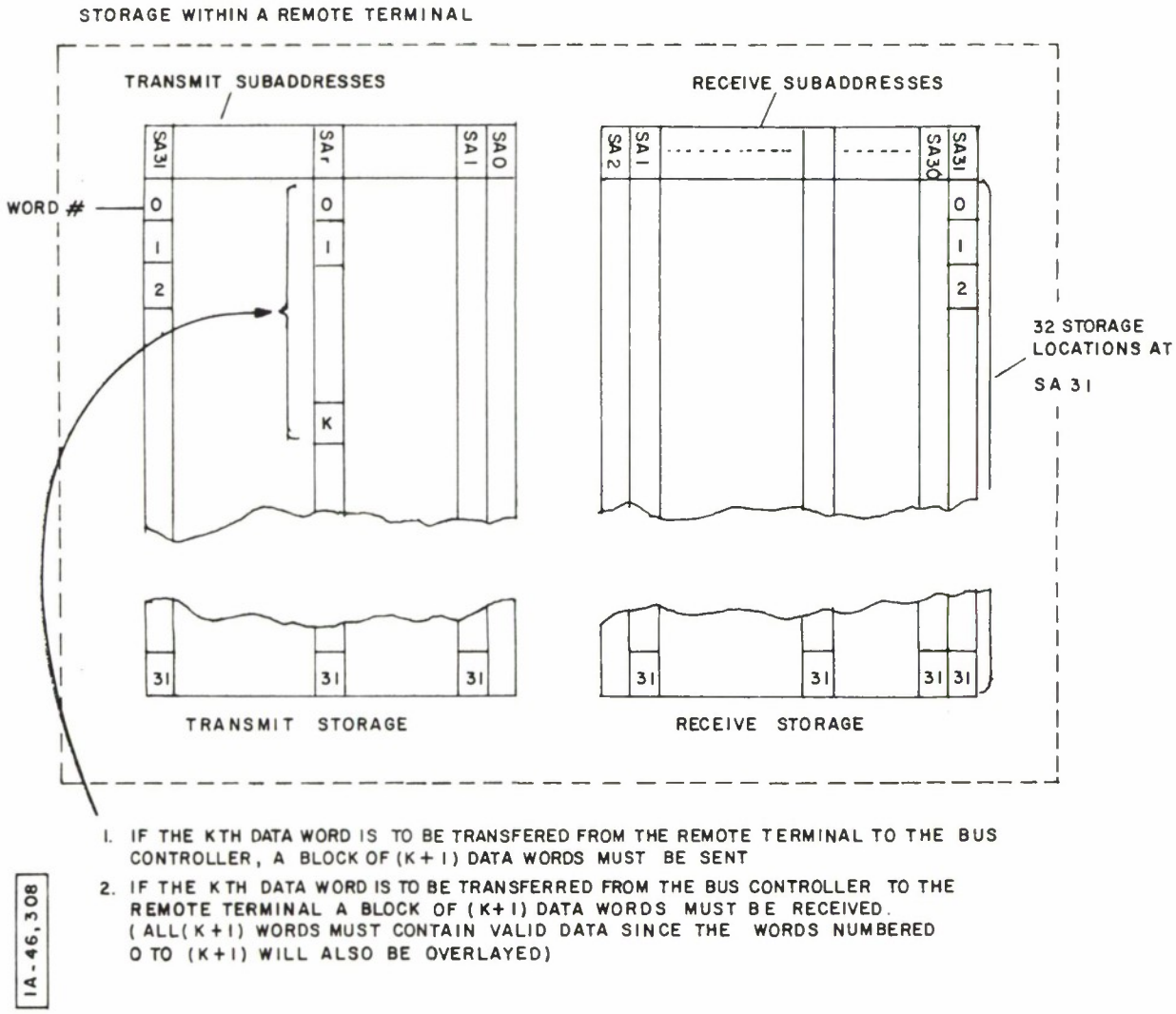


Figure 7 NOTATION USED IN DISCUSSING STORAGE WITHIN A REMOTE TERMINAL

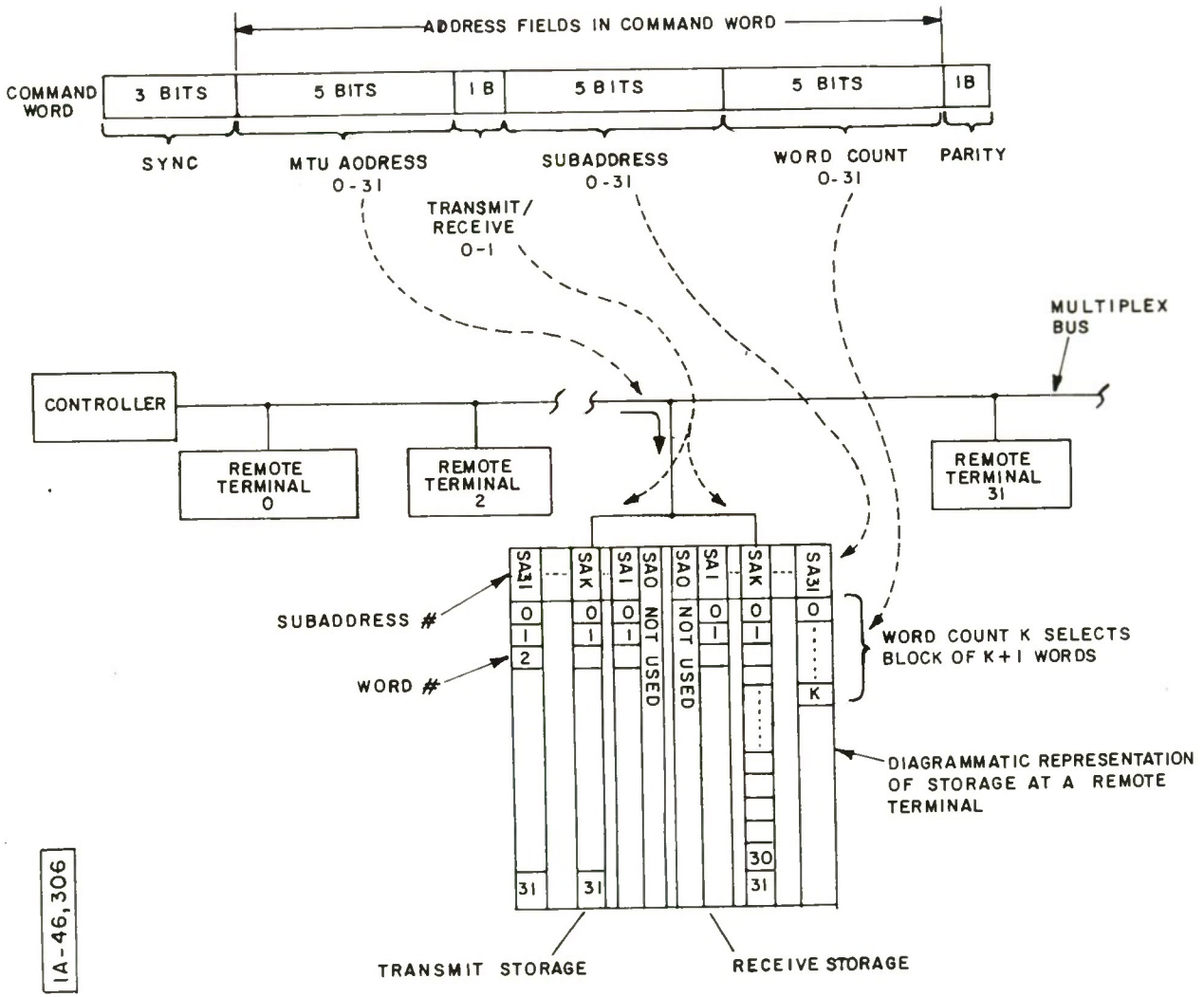


Figure 8. CONCEPTUAL REPRESENTATION OF DISTRIBUTED MEMORY ASSOCIATED WITH A STANDARD BUS

requesting that a block of (r+1) Data Words be transferred to the controller, the required word being the last--the rth--in the block.

The constraint of transferring a block of (r+1) Data Words in order to access the rth has the potential to markedly decrease the available information capacity of the bus. For example, if the bus controller requires a DW in the fifteenth location of a subaddress, then a block of 16 Data Words must be transferred. The useful information capacity of the message interchange would be only 6 percent of that assumed in the available capacity curves of Figure 4. It may be objected that a pessimistic picture is being presented by selecting the fifteenth word, rather than the third, say; the latter would give a useful information capacity of 25 percent of that assumed in Figure 4. However, examinations of these curves indicate that the upper bounds for the shorter blocks of data words are significantly lower than those for the longer blocks; thus, the net result is still poor bus utilization.

3.3.2 Increasing Information Density Within a Message Block

One approach to circumventing this problem is to organize the information flow between the bus controller and the equipments serviced by the bus so that the block of Data Words--rather than the single DW terminating the block--contains useful information for the recipient. While such a technique is self-evident and has been automatically adopted in some bus configurations, difficulties arise which tend to offset the anticipated increase in information density within a message block. These problems stem from the flexibility of information transfer which the bus is intended to promote; namely, a range of rates at which the equipment parameters can be sampled, and multiple users of subsets of the set of DWs generated by a subsystem.

Consider a specific example. In allocating the storage at a remote terminal amongst the equipments being serviced, it would seem reasonable--as a first pass--to allocate a single subaddress to a navigational subsystem, say; the intent being that all the Data Words generated by that unit would be stored in the 32 locations associated with that subaddress, and updated in real time as the requirement demands. Due to the intrinsic physical characteristics of the various parameters which the Data Words represent, their bandwidth--and hence their update rates--will differ one from another. For example, the control information defining a band switching operation will have different response time characteristics from range and bearing data, and hence will not require sampling at the same rate by the user. However, it has already been shown that selective interrogation of DWs within a subaddress can lead to inefficient use of the bus.

If for convenience of implementation it is decided that all parameters of the unit should be transferred to the user at the maximum rate, then there will be an effective reduction in the available information capacity of the line. The significance of the reduction is a function of the particular equipment, number of users, etc., and cannot be concisely generalized. However, to illustrate the effect, consider an equipment which has four parameters requiring sampling by a user at 8, 4, 2, and 1 times per second, respectively. If each parameter requires a separate DW, then the message transferring the information to the user will contain a block of four Data Words, and it will be sent eight times per second. The redundancy of such a transfer would be approximately 50 percent--a sharp reduction of the capacity presented in Figure 4.

3.3.3 Allocation of Multiple Subaddresses to a Subsystem

To avoid the potential problem outlined above, it has been suggested that the parameters output by a subsystem be grouped according to sampling rate, and each subdivision be allocated a separate subaddress, see Figure 9. Each subaddress could then be sampled at its appropriate rate and all words in the message block would be non-redundant information. This would overcome the problem of redundancy if the word transfers for a given subsystem were between a unique source-sink pair, or alternatively between several source-pairs with the same information transfer requirements. However, in general, this will not be the case; various "sink" subsystems will likely use different subsets of the data/parameters generated by a "source" subsystem, see Figure 10.

The discussion above relating to multiple sampling rates is equally applicable to the problem of multiple users. Analogous to the flow of redundant information due to oversampling, is the transfer to a user of all the parameters generated by a source subsystem, rather than only the subset which it needs. The solution is also similar; the grouping of the subsystem's output into subsets used by unique source/sink pairs, and then the allocation of a subaddress to each subset. However, it should be noted that the number of locations occupied at the remote terminal may now be increased due to the need for multiple copies of the Data Words required by more than one user.

A conceptual allocation of storage at a remote terminal unit for an equipment producing parameters of various sampling rates, working with a number of users requiring only subsets of the data items, is shown in Figure 11. It can be seen that in attempting to reduce information redundancy on the bus there has been profligate usage of the 31 subaddresses available to each remote terminal. Once again, the significance of this depends on several factors.

IA-46,31D

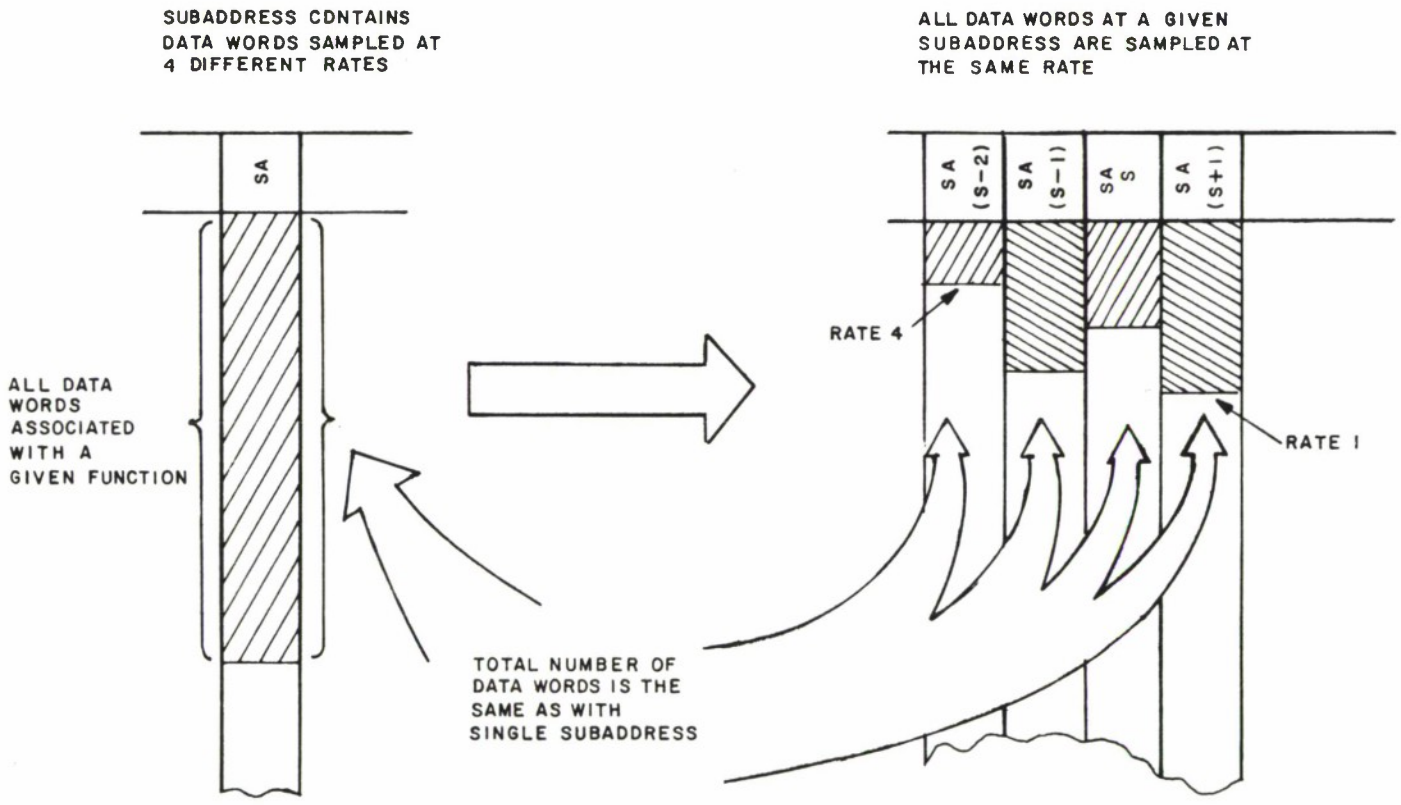


Figure 9 ORGANIZATION OF OUTPUT FROM A GIVEN FUNCTION BY SEPARATE SUBADDRESSES FOR EACH SAMPLING RATE

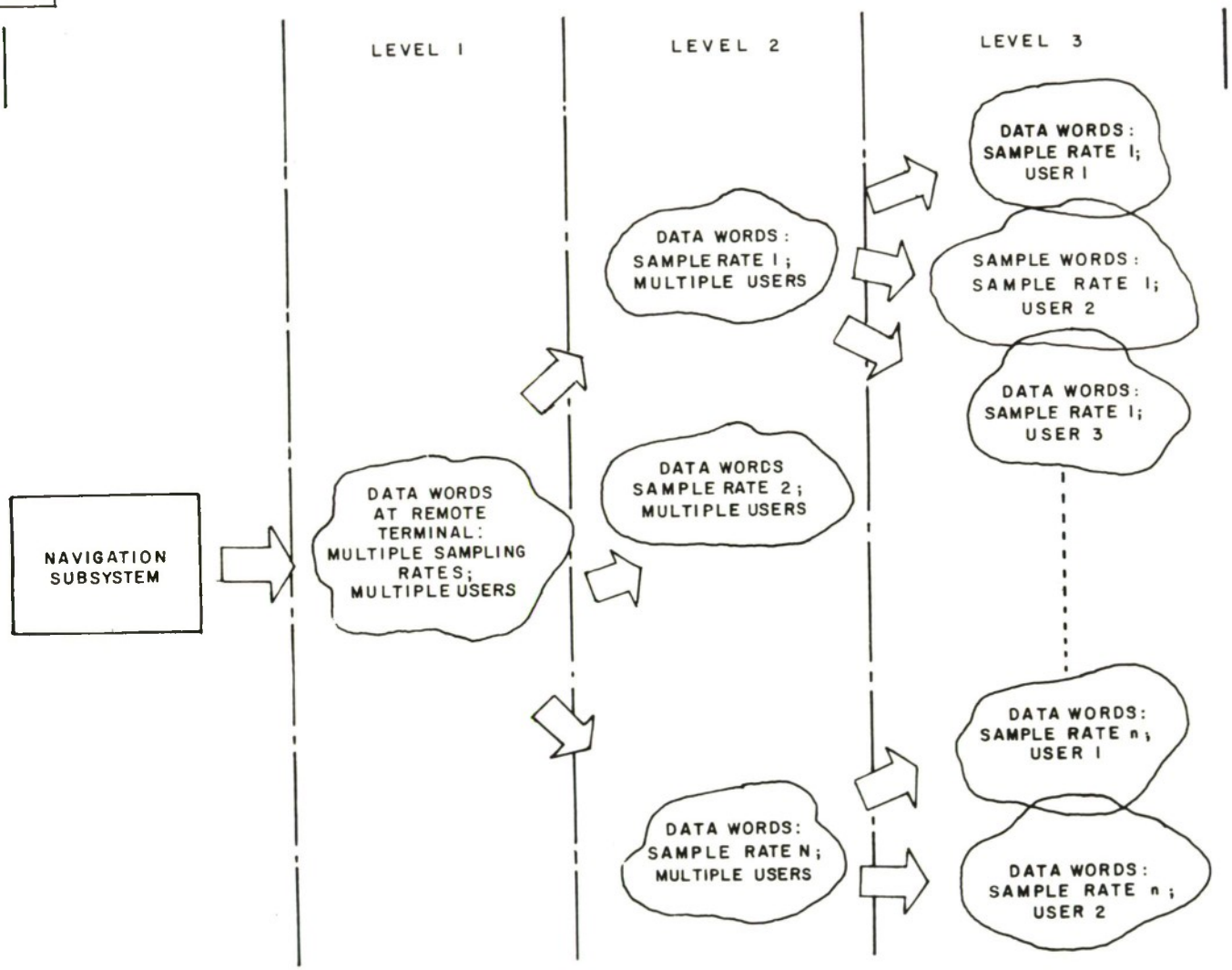


Figure 10. CONCEPTUAL SUBDIVISION OF OUTPUT INFORMATION FROM A SOURCE SUBSYSTEM SERVICED BY A REMOTE TERMINAL

IA-46,309

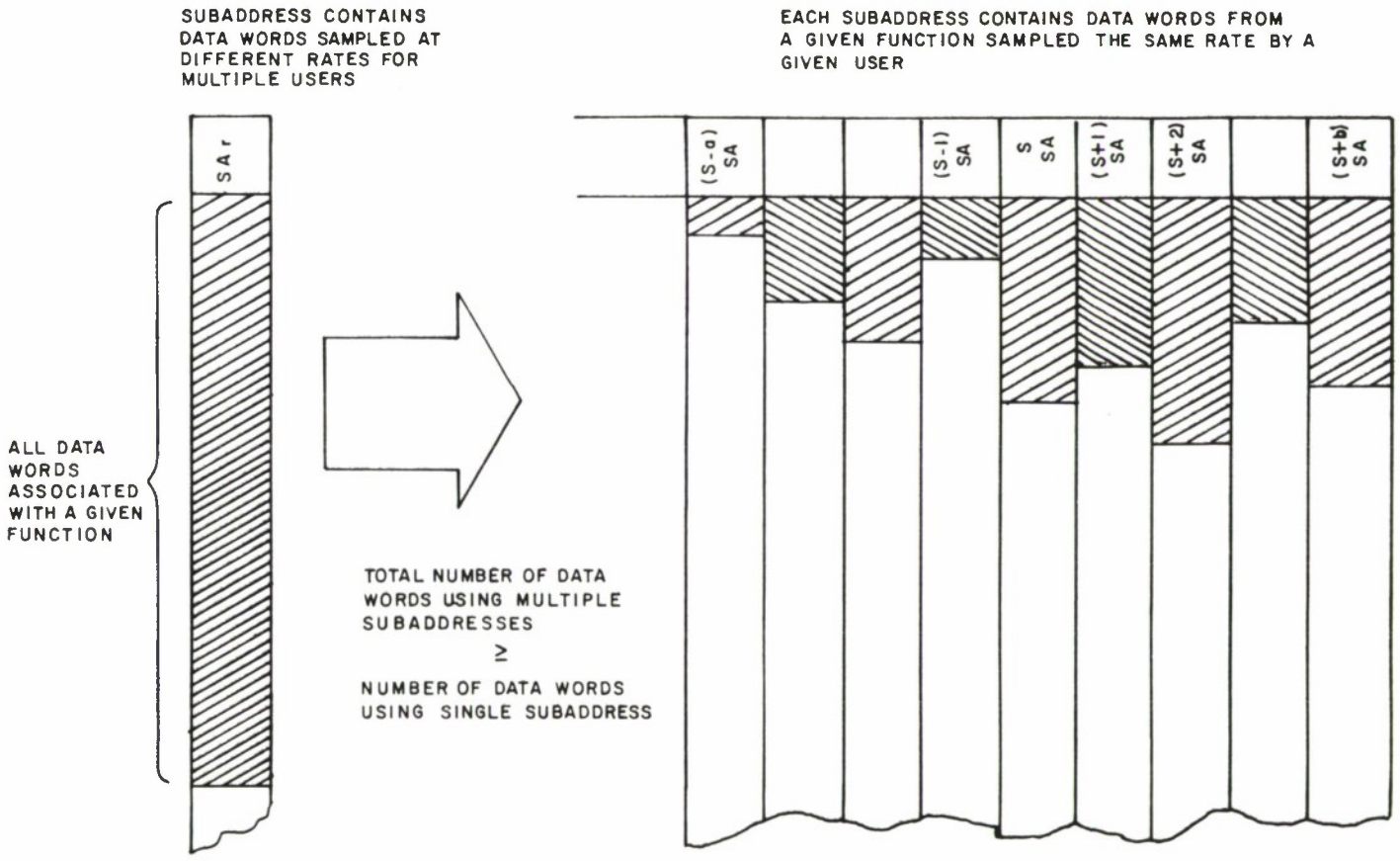


Figure 11. ORGANIZATION OF OUTPUT FROM A GIVEN FUNCTION BY SEPARATE SUBADDRESSES FOR EACH SAMPLING RATE/USER PAIR

For example, if the remote terminal in question is intended to service a concentration of equipment located in an equipment bay, then it is likely that there will be a dearth of subaddresses, and the allocation of several to a subsystem could result in the use of additional remote terminals, or even require an increase in the number of buses used. If, on the other hand, the RT is servicing few subsystems, the need for a multiplicity of subaddresses for each may not be a problem.

Another point is that the original intent of increasing the information density in a block of words has led to a decrease in the number of Data Words per message from that which might have been anticipated when considering the total DW output of the equipment. Thus, the goal of increasing the effective information capacity of the bus by increasing the information density of a block of Data Words is thwarted by the lower information capacity resulting from the use of shorter messages.

3.3.4 Another Attempt to Increase Message Length

It was originally suggested that a given subsystem serviced by the bus should be allocated a single subaddress for data storage. The potential inefficiency of this approach--in terms of available information capacity of the bus--leads to the suggestion that several subaddresses per subsystem would be preferable. This in turn indicated potential inefficiencies arising from the shorter message length that would result, and a possible shortage of subaddresses, requiring an increase in the number of remote terminals required. To offset both of these problems, it has been proposed that the unique subsystem--subaddress(es)-- combinations be abandoned. The idea would be to maintain the sample rate and subset subdivisions outlined above, but to pack information of the same type from other equipments into the common subaddress. The configuration would be similar to that shown in Figure 11 but without the constraint of all Data Words being generated by the same source function. The packing could be by both Data Words in message block and by bits in a Data Word, see Figures 12 and 13. Such an approach could possibly result in more efficient bus usage by eliminating, or reducing, the transfer of redundant information, while permitting the use of longer messages--containing information from several subsystems serviced by the same remote terminal.

The primary disadvantage of this technique cannot readily be expressed quantitatively; however, it would significantly impact the buses' flexibility. One of the guiding tenets throughout the design of the processing associated with the transfer of information between units serviced by the bus has been to partition the data flow so that changes in the information requirements on one source/sink pair do not impact other units on the bus. The purpose

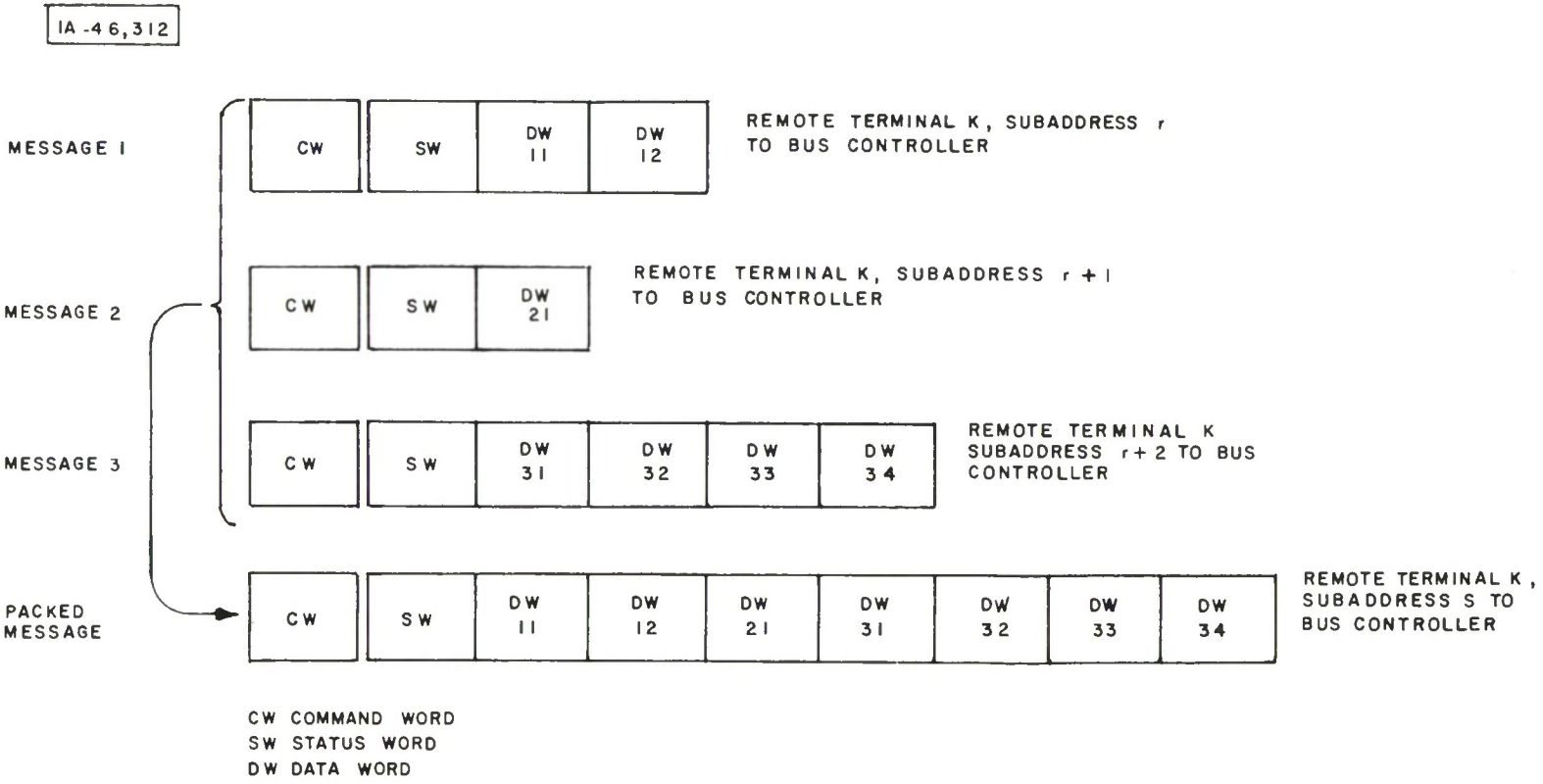


Figure 12. MESSAGE PACKING

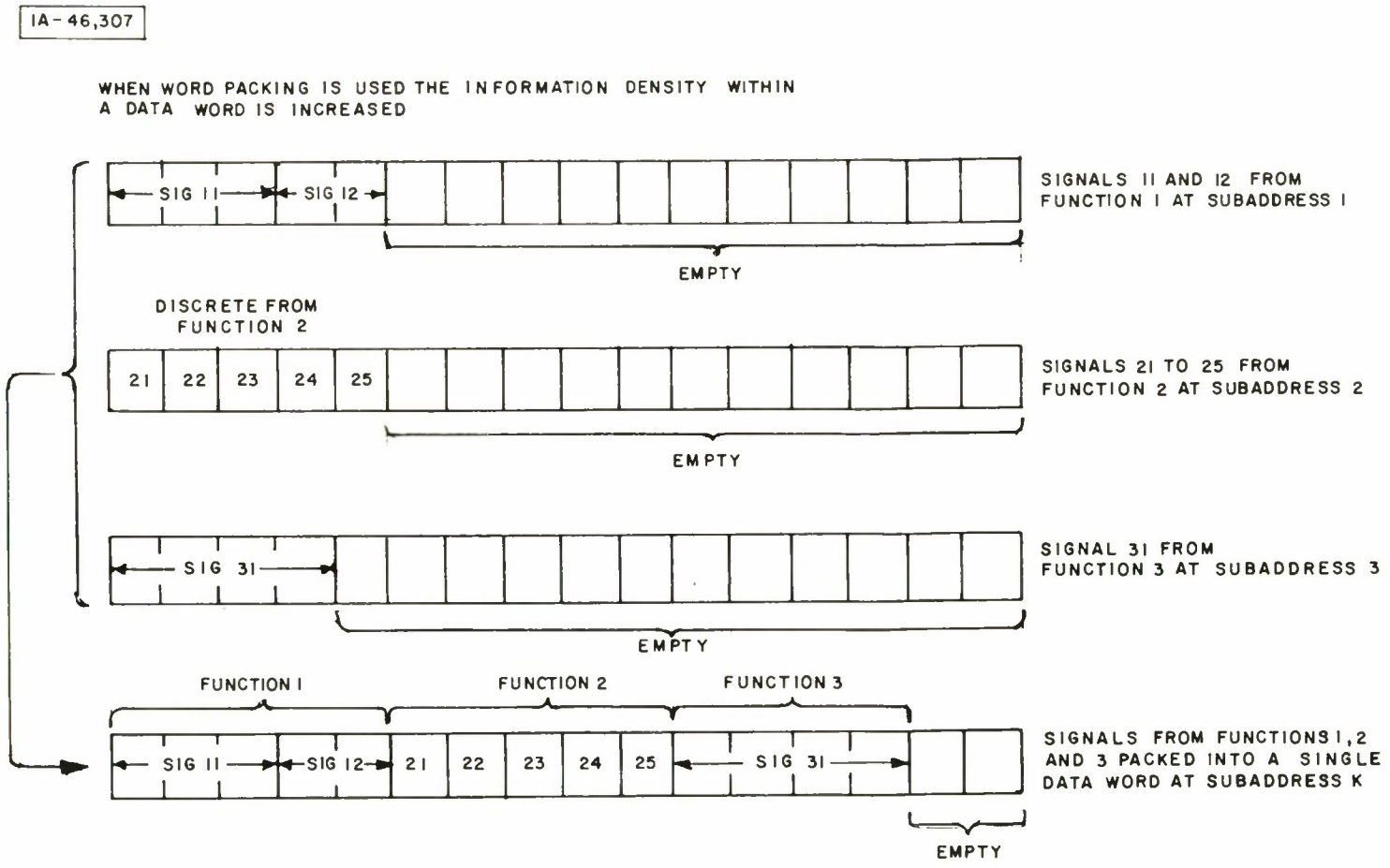


Figure 13. WORD PACKING

of this is to ensure that the bus control software can readily be adapted to changes in the equipment complement being serviced, without extensive modifications to the processing involving the data flow to other source/sink pairs in the avionics suite. The storage of information from several subsystems at a common subaddress--or set of subaddresses--would jeopardize this goal of separability. In general, a processing routine used to pack/unpack a message block or Data Word, and to collect/distribute the information it contains is dependent on the source-sink pairs involved. It is conceivable that some measure of standardization in this area might formalize the changes in processing incurred by the inclusion, or removal, of equipment in the avionics suite. However, until such procedures are established, it is desirable in the interest of flexibility, i.e. in the ability to adapt to changes in an equipment complex with minimum modification to the collection and distribution segment of the bus control software, to organize the storage at the remote terminal to permit easy separability of data flow between the source-sink pairs.

3.3.5 General Comment on Storage Organization at a Remote Terminal

The presentation given above is relatively simplistic, and various organizations of particular classes of data, for example, parameters of different bandwidths, can partially offset some of the inefficiencies outlined above. However, it is not the intention to exhaustively discuss these particular aspects of the data transfer between units, but rather to indicate that the available information capacity of the bus as graphed in Figure 4 is an upper bound that cannot readily be approached without considerable detailed design effort.

If efficient usage of the bus capacity is of academic interest--due to under utilization by the equipment complex which the bus services--then the storage organization to be used can be selected by criteria other than that of available information capacity. However, if information transfer capacity is of significance, then a host of interacting factors involving hardware, software, and operational factors must be considered. Any practical attempt to quantitatively assess the sensitivity of the information capacity of the bus to a range of permutations of these conditions would necessitate the development of a relatively complex simulation.

3.4 Temporal Aspects of Signal Information Transfer by an Avionics Bus

The following section is included not because of any particular constraint imposed by MIL-STD-1553 (USAF), but rather because little is said on the time related aspects of information transfer even

though they can have significant impact on bus standardization and design. The presentation of the material is in the form of an annotated listing of some of the different types of information--in regard to their temporal characteristics--that might be placed on the bus, with some discussion, where appropriate, as to how those factors might influence the system design.

In considering some of the general time-related characteristics of information flow on the bus, it is appropriate to start with the physical event, or process, that the data describes. Of the set of descriptors that define a phenomenon, the two that are considered here are the time of occurrence of an event--its epoch--and a measure of its dynamic characteristics--its bandwidth. No attempt will be made to discuss the very real subtleties in these concepts, and an heuristic discussion based on a general understanding of what these parameters describe should be sufficient for the present purpose. In this context then, the function of the information distribution system is to transfer data between a source-sink pair in a manner that is compatible with the temporal characteristics of the source and/or the needs of the user. The performance of the transfer network cannot enhance the intrinsic properties of the source process; for example, sampling its output at above the Nyquist rate will not increase its bandwidth. On the other hand, the distribution system can distort the available information; an unknown delay--fixed or variable--can cause uncertainty in an epoch; undersampling can misrepresent the dynamic characteristics. However, there is nothing sacrosanct about the characteristics of the source process. If a distorted representation is adequate for the purpose of the user, then it is pointless to load the bus with the additional data resulting from sampling to match an unnecessarily large bandwidth. The crucial factor is that the standard bus is intended to be a tool for the system designer; while a wide range of capability is desirable, it is equally important that all pertinent aspects of its performance be defined so that a user can employ the distribution network for his own ends. The following subsections differentiate between some of these uses, and indicate their relationship to bus characteristics.

3.4.1 Control Information; Human in Loop

One class of information that is suitable for transmission on the bus is the control signals initiated by an operator's manipulation of switches and/or dials. The acceptance of human response times within the loop ensures that the bandwidth of the process is relatively narrow (~1 Hz), and can readily be handled by the signal detection and distribution system operating at low sampling/message rates for each control function. Analyses of typical avionics suites have indicated that this type of data comprises a large proportion of the information flowing between the

equipments, and thus gives credence to the suitability of a bus as the communication medium.

3.4.2 Control Information; No Human in Loop

When the control loop does not contain a man-activated operation, more care is necessary to determine what temporal characteristics of the source must be reproduced. For example, a Mach 2 aircraft moves approximately 2000 fps, thus some functions which are highly range sensitive might require sampling at such a high rate that they absorb too great a fraction of the bus capacity. Even if the system designer is prepared to sample at the required rate, and thus preserve the dynamic description of the source, the "real-time" nature of the data must be maintained. For example, delaying the data by buffering the message stream in a first-in first-out memory prior to placing the messages on the line, might be a desirable and acceptable design approach when handling data that can tolerate the delay; whereas in other cases it might render the data worthless. Fortunately, the number of functions in which the foregoing considerations are significant appears to be small. However, the standard bus should be sufficiently well defined that a system designer has enough information to make assessment in any particular case.

3.4.3 Explicit and Implicit Time Tagging

In the previous sections the temporal characteristics of the output from the source were of varying degrees of importance, but in neither case was the actual time--in contradistinction to the occurrence--of an event of significance. However in some cases, for example when navigational data from diverse sources are being combined, it may be necessary to associate time labels with the various events. It should be stressed that the epoch which is being considered is that of an event of the source process; not the time at which its output is received by the user, nor processed by the controller, nor any one of the many other phases of its existence before its identity is lost on being merged with other data. The constraints on the bus design arising from the need to handle "epoch sensitive" data can range from negligible to significant, depending on the accuracy required, nature of the source process, and many other factors.

3.4.3.1 Explicit Time Tagging. While an obvious approach to handling epoch sensitive data is to attach a time label to the source output, the method of implementation is less self-evident. For example, should the source subsystem itself be required to supply the tag, or should it be a function of the sampling operation within the remote terminal? In both cases the load on the bus will be increased for this class of information; however, the impact on

the terminal design would be quite different. Again, what are the relative constraints on time tags originating at different remote terminals? At present the bus controller and the remote terminals operate asynchronously, and no explicit mechanism is included for the correlation of events at various locations; will this suffice for future applications projected for a standard bus?

3.4.3.2 Implicit Time Tagging. Another class of data that may constrain the bus design is that in which a constant interval between samples is assumed by the user. That is, if the initiation of the sequence of samples is at time t_o, the implicit time tags are $t_o + \Delta t$, $t_o + 2\Delta t$, ...etc. where Δt is the nominal sampling interval. The present standard permits bus designs which could impose a jitter on the data sent to the user; whether this is significant would depend on the specifics of the case. If some form of correction is necessary, explicit time tags can be associated with the nominally periodic samples; however, the additional data processing involved in the use of non-uniform data can be considerable.

3.4.4 Data for Post-Flight Analysis

If both time of occurrence and dynamic representation of the source output is of importance, but the information is not required for real-time operation, then the specifications for the network are less demanding than those outlined in the previous sections. An example of such a function is the recording of data for post-flight analysis, such as might be involved in a reconnaissance mission. An accurate reconstruction of the flight path of the vehicle may require precise epoch and relatively high bandwidth data; however, in the course of its transfer from source to sink, a substantial known delay could be tolerated without degrading the quality of the reconstituted track.

3.4.5 Summary on Temporal Aspects of Signal Transfer by an Avionics Bus

The foregoing sections provide only a superficial treatment of some of the temporal problems that arise when signals are transferred between source-sink pairs on an avionics bus. Other classes of data could have been included; some of the problems anticipated could be shown to be non-existent under some conditions and severe under different circumstances, and so on. However, as was stated in the introduction, the aim of Section 3.4 is not to provide an exhaustive treatment of the subject, but rather to alert the system designer to an aspect of bus design that is only briefly touched upon in the military standard, and yet can have considerable bearing on the compatibility of "standard bus" designs.

4.0 SUMMARY AND CONCLUSIONS

Since MIL-STD-1553 (USAF), defining a preferred configuration for a TDM avionics bus, was issued in August 1973, MITRE has been critically evaluating its content. Part of the task has been the development of an experimental bus which embodies most of the standard's requirements. In the course of engineering the software for the message control function, several factors emerged which were not immediately apparent on first reading the standard. In some areas joint consideration of requirements gave rise to severe constraints on the bus network. In other instances there was sufficient ambiguity to warrant the belief that buses designed in accordance with the standard could have different performance capabilities in areas pertinent to the internal transfer of data, and moreover, be incompatible for the interchange of data one with another.

Four main topics have been discussed:

- Bus capacity. The requirements on the message formats and bus protocol that are contained in the standard have been combined to determine an upper bound on the capacity of the bus available for moving data between source-sink pairs. The available capacity is shown to be a strong function of the number of Data Words in a message, and is at best less than 75% of the nominal bus capacity.

- Time constraint on message handling. The implicit requirement on the bus capacity, and the explicit definition of the message formats, have been combined to give an estimate of the minimum time available for the bus controller to handle successive messages when the bus is being operated at 100 percent duty cycle. A typical general purpose airborne computer cannot support the task, and a special purpose processor of considerable sophistication is necessary if the maximum message rate permitted by the standard is to be realized.

- Subaddresses and Data Word accessibility. The standard format of the Command Word defines the addressing mechanism that must be used by the bus controller to obtain information from a remote terminal. Data Words must be accessed by blocks rather than separately. Consequences of this have been investigated and shown to have the potential of reducing the useful bus capacity significantly below the upper bounds dictated by overhead considerations.

- Temporal considerations of information transfer on the avionics bus. Since all data transferred on the bus is sensitive, to some degree, to misrepresentation of its epoch

and bandwidth, some consideration was given to this aspect of bus design. Although the investigation was relatively cursory, it is apparent that because the standard gives such superficial guidance in this area there is a very real possibility that "standard" buses would differ significantly in their ability to transfer the temporal characteristics of a source process to the user.

The generation of MIL-STD-1553 (USAF) was a major step forward in standardizing the application of TDM buses to aircraft. However, experience is showing that uncertainty regarding its intent still exists, and must be removed before the goal of meaningful standardization can be achieved.

APPENDIX I

A.0 CALCULATION OF UPPER BOUND ON INFORMATION CAPACITY OF A STANDARD BUS

The message and word formats, together with the bus protocol, defined in MIL-STD-1553 (USAF), result in some fraction of the nominal capacity of the bus being absorbed in the transfer of "overhead" data. Curves quantifying this effect are given in Figures 4 and 5 in the body of this report. The following calculations are given to permit the reader to confirm his understanding of the terms used.

A.1 Controller/Remote Terminal Transfers

The word and message formats of the Controller/Remote terminal transfers are given in Figures 2 and 3. For an N Data Word transfer, the total bit requirements are:

Information bits:	16N	
Overhead bits:	2 x 20	Command Word and Status Word
	4N	Sync and Parity on N Data Words
"No signal" bits:	t_{sep}	Intermessage gap
	t_{sep}	Intercomponent gap

Fractional information capacity is

$$\frac{16N}{(N+2)\ 20 + 2t_{sep}} \qquad \text{CU/RT and RT/CU}$$

Fractional overhead capacity is

$$\frac{4N + 40}{(N+2)\ 20 + 2t_{sep}} \qquad \text{CU/RT and RT/CU}$$

Fractional "no signal" capacity is

$$\frac{2t_{sep}}{(N+2)\ 20 + 2t_{sep}} \qquad \text{CU/RT and RT/CU}$$

A.2 Remote Terminal to Remote Terminal Transfers

The word and message formats of the RT/RT transfers are given in Figures 2 and 3. For an N Data Word transfer, the total bit requirements are:

Information bits:	16N	
Overhead bits:	4 x 20	Two Command Words and 2 Status Words
	4N	Sync and parity on N Data Words
"No signal" bits:	t_{sep}	Intermessage gap
	$2t_{sep}$	Intercomponent gap

Fractional information capacity is

$$\frac{16N}{20\ (N+4) + 3t_{sep}} \qquad \text{RT/RT}$$

Fractional overhead capacity is

$$\frac{4N + 80}{20\ (N+4) + 3t_{sep}} \qquad \text{RT/RT}$$

Fractional "no signal" capacity is

$$\frac{3t_{sep}}{20\ (N+4) + 3t_{sep}} \qquad \text{RT/RT}$$

The relationships given in Sections A.1 and A.2 are graphed in Figure 4 for--the number of Data Words in a message, N--ranging between 1 and 32, and for t_{sep} = 2 and 5 microseconds.

A.3 Upper Bound on Message Rate on a Standard Bus

The upper bound on the message rate on a standard bus is obtained directly from the total number of bits in a message sequence--see Sections A.1 and A.2 above.

Maximum number of message sequences per second is:

$$\left[20\ (N+2) + 2t_{sep}\right]^{-1} \qquad \text{CU/RT and RT/CU}$$

$$\left[20\ (N+4) + 3t_{sep}\right]^{-1} \qquad \text{RT/RT}$$

These relationships are graphed in Figure 5 for N between 1 and 32, and for t_{sep} = 2 and 5 microseconds.

REFERENCES

1. Aircraft Internal Time Division Multiplex Data Bus, MIL-STD-1553 (USAF), 30 August 1973.

2. Digital Avionics Group, "Radio Information System Architecture," ESD-TR-75-70, July 1975.

3. P.R. Cloud, "An Outline of the Applications Software for the RIDS Experimental TDM Bus," ESD-TR-75-78, September 1975.