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Evaluation and Mission-Specific Optimization of Satellite Packet Telemetry Protocol for Use on DoD Flight Test Ranges

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EVALUATION AND MISSION-SPECIFIC OPTIMIZATION OF SATELLITE PACKET TELEMETRY PROTOCOL FOR USE ON DOD FLIGHT TEST RANGES

THESIS

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Abstract
The DoD test range community has come to the realization that its telemetry abilities are obsolete. Efforts are therefore underway to improve telemetry systems at DoD test ranges. The overall objective of this project was to evaluate the practical use of the CCSDS packet telemetry protocol in DoD test ranges and determine the configuration that would maximize performance based on mission requirements. A secondary objective was to compare the CCSDS and ATM protocols in order to substantiate further exploration of using ATM in future DoD telemetry systems. Modeling and simulation of the CCSDS protocol showed a correlation between three CCSDS parameters and the resulting throughput and data quality performance. Flight tests confirmed the correlation between the CCSDS parameters and the resulting protocol performance, and narrowed in on the CCSDS configurations that would maximize data throughput, data quality, or provide a combined "best of both worlds" solution. In general, flight test results matched those of the modeling and simulation work. Data collected also indicated that performance of the ATM protocol is sufficiently close to that of CCSDS to warrant further investigation of using ATM on test ranges. ATM offers the military user straightforward interoperability with civilian systems/networks.

Subject Terms
CCSDS (Consultative Committee for Space Data Systems), Asynchronous Transfer Mode, telemetry, packets, protocol, Reed-Solomon code, packet protocols

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THESIS

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BethAnn Trapp

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Abstract

The DoD range community has recognized that its Telemetry (TM) link abilities are quickly becoming obsolete. To date, the 40-year-old technology used in its telemetry systems has sufficed for DoD test ranges. However, with increasingly advanced weapons systems coming on-line, this "old" technology is no longer meeting the demands of modern flight-testing. There is an escalating amount of data that needs to be transmitted to ensure safety of flight and monitor vehicle performance, and mounting pressure to perform testing faster and more efficiently. In addition, the portion of the radio frequency spectrum allotted to flight testing shrank significantly in 2001 when these frequencies were reallocated to support commercial telecommunications satellites. For these reasons, efforts are underway to improve TM systems at DoD test ranges. Over the past 15 years, the Consultative Committee for Space Data Systems (CCSDS) has recommended the establishment of a common framework for data services of spacecraft telemetry systems. The CCSDS recommendation, which was officially named a Range Commander's Council/Inter-Range Instrumentation Group (RCC/IRIG) standard in 2001, has been in limited use in the space community and will likely be applied in the test range community. The overall objective of this project was to evaluate the practical use of CCSDS in the DoD test range environment and determine the configuration of CCSDS protocol parameters that would maximize CCSDS performance based on mission requirements. A secondary objective was to compare the performance of CCSDS to the Asynchronous Transfer Mode (ATM) protocol in order to substantiate further exploration

of using the ATM protocol, alone or in conjunction with CCSDS, in future DoD telemetry systems.

Modeling and simulation of the CCSDS packet telemetry protocol was conducted at the Air Force Institute of Technology at Wright-Patterson AFB, during Jul-Nov 2000. This work showed a correlation between three specific CCSDS protocol parameters and the resulting throughput and data quality performance of the protocol. Flight tests were then conducted by the USAF Test Pilot School at the Air Force Flight Test Center (AFFTC), Edwards AFB, CA, from 5-31 October, 2001, using a Sabreliner T-39A passenger jet. Preliminary results confirmed the correlation between the previously identified CCSDS parameters and the resulting protocol performance. After further testing, the team was able to narrow in on the combination of parameters that would maximize data throughput, data quality, or provide a combined "best of both worlds" solution. In general, flight test results matched those of the modeling and simulation work.

Finally, data collected with the CCSDS parameters set to mimic the data-to-overhead ratio of the ATM protocol indicated that the throughput and data quality performance of the ATM protocol is sufficiently close to that of the CCSDS protocol to warrant further investigation of using the ATM protocol in the test range environment. Unlike CCSDS, ATM offers the military user interoperability with civilian systems/networks.

EVALUATION AND MISSION-SPECIFIC OPTIMIZATION OF CONSULTATIVE COMMITTEE FOR SPACE DATA SYSTEMS (CCSDS) PACKET TELEMETRY PROTOCOL RECOMMENDATION

CHAPTER I - BACKGROUND & PROBLEM STATEMENT

1.1 Background

The sampled data system technology used in telemetry systems within the Department of Defense test community is more than 40 years old [14]. Figure 1 illustrates the current Pulse Code Modulation (PCM) telemetry scheme. Typically, multiple data sources within the test vehicle each produce and transfer a bit stream of data into an on-board multiplexer. Operating in a Time Division Multiple Access (TDMA) mode, the multiplexer organizes the incoming bit streams into ***major frames*** consisting of a number of ***minor frames*** (up to 256 minor frames combine to form one major frame). The frame structure is preprogrammed for each mission and relatively static between missions. Minor frames can range in size from a few hundred bits up to 8 Kbits, but once the size is set it cannot be easily changed. The minor frame consists of a header (primarily a synchronization pattern) and a fixed number of payload slots. Each data source on the aircraft is assigned one or more slots in the major frame. As with frame structure, slot assignments are preprogrammed and fixed during a mission. If a particular data source is not operational, or is not producing valid data at some point in time, its assigned slots are filled with arbitrary filler bits.

In order to maintain a continuous flow of bits, the multiplexer is clocked at the bit rate of the RF downlink. The bit rate of the RF link can vary from 1-20 Mbps, but for practical considerations, including range spectrum allocations, the link typically operates at 1-5 Mbps. Once received, minor frames are sent to a de-multiplexer where individual data streams are reconstructed and forwarded to the appropriate data acquisition applications. There are no redundant transmission capabilities; if critical data is corrupted or lost during the downlink process, on-board recorders are used to reconstruct the bit stream, or if they are not available, the flight test is repeated to recreate the data.

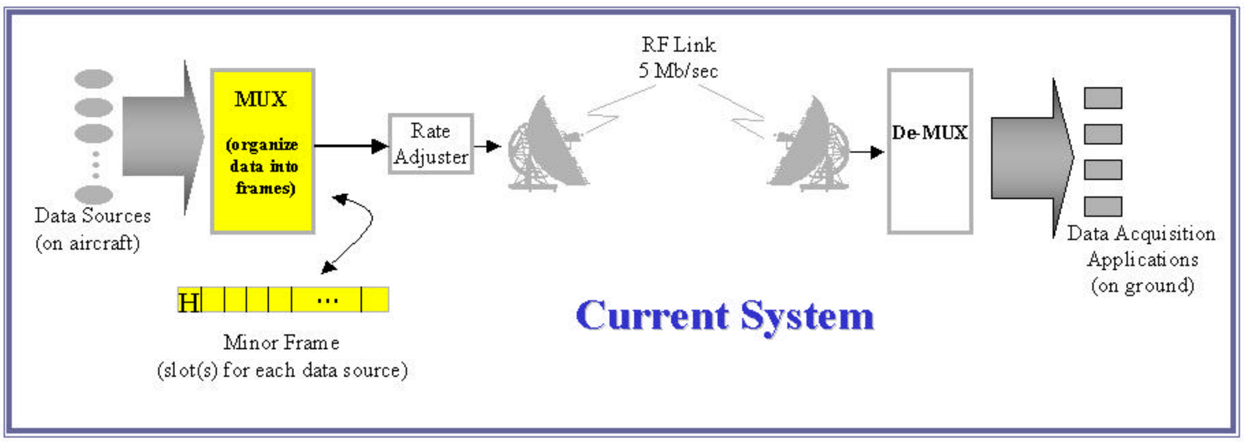

Figure 1. Current DoD Telemetry System

There are several drawbacks to the current PCM telemetry scheme. The static nature of the minor frames (specifically, the permanent slot assignments and use of filler bits) is inefficient and limits effective data throughput. Prioritization is accomplished only by assigning in advance a large number of slots to a particular data source. The allocated RF bandwidth is invariably less than required and continues to shrink as portions of the DoD Test and Evaluation frequency bands are reallocated to support commercial telecommunications. In an unmodified PCM system, all data from all sources is transmitted to ground sites whether or not that data is being used or requested. Additionally, any data that is lost or corrupted during transmission must be restored from tape or recreated. While in flight, users on the ground have no means of re-tasking or adjusting data sources on the aircraft, which often means additional costly flight tests.

Although there are many areas where improvements can be made, the focus of this research is the replacement of the major and minor frames with a modern, more efficient packet telemetry scheme. Over the past 15 years, the Consultative Committee for Space Data Systems (CCSDS) has recommended the establishment of a common framework for data services of spacecraft telemetry systems [4]. The CCSDS recommendation, which became a Range Commander's Council/Inter-Range Instrumentation Group (RCC/IRIG) standard in 2001, has been in limited use in the space community and will likely be applied in the test range community. Therefore, CCSDS is the packet telemetry scheme examined in this thesis study. The conclusions reached in this study can be directly applied to other areas of current research, including efforts to apply Asynchronous Transfer Mode (ATM) technology to telemetry at various test ranges [13].

1.2 Problem Statement

The goal of this research is to evaluate the practical use of the Consultative Committee for Space Data Systems (CCSDS) packet telemetry standard in the Department of Defense (DoD) test range environment. Three CCSDS parameters have been identified as having a strong influence on the protocol's performance. These parameters are transfer frame size, source packet length, and Reed-Solomon error-correction encoding. The effects these parameters have on system throughput and data quality is established and guidance provided to allow optimization of the protocol to meet user specified quality of service requirements. CCSDS protocol performance is also compared to that of the Asynchronous Transfer Mode (ATM) protocol in an attempt to substantiate further exploration into using the ATM protocol, either alone or in conjunction with CCSDS, in future DoD telemetry systems.

1.3 Scope

Data-producing subsystems on an aircraft using the CCSDS standard generate variable length ***source packets***. A CCSDS processor then segments the packets to produce a stream of fixed length ***transfer frames***, which are subsequently transmitted to the ground. Generally, this data has certain transfer requirements, or Quality of Service (QoS) parameters, such as throughput and reliability. Depending on the type of data being transferred, these QoS parameters can vary. For example, video data should be transferred with minimum delay but can tolerate occasional data losses. On the other hand, memory data, such as GPS location data, cannot tolerate any loss of data but can usually accept some delay [23]. Performance of the system can be defined according to several metrics. These include, but are not limited to, effective data throughput, data quality, channel utilization, and data latency. The focus of this research is choosing *a priori* the most advantageous CCSDS source packet and transfer frame lengths, with respect to throughput and data quality for a given mission. Given the limited RF spectrum allocation, users in the test range community have a strong interest in maximizing channel usage [13]. This research therefore concentrates only on those combinations of CCSDS parameters that provide near-100% channel utilization[1]. Data latency is not directly evaluated in this study although it would be an important factor in real-time applications.

Evaluation of source packet and transfer frame length versus throughput and data quality is done via computer simulation using OPNET network simulation tools [15]. A model of the current telemetry system is built in OPNET incorporating representative channel error-rate characteristics of Edwards Air Force Base (AFB), California. Varying source packet and transfer frame lengths are evaluated as detailed in Chapter III. Validation of the study's results is carried out via flight test as part of the USAF Test Pilot School (TPS) curriculum. The Advanced Range Telemetry (ARTM) office located at Edwards AFB is heading up the overall project and was responsible for assembly of the actual telemetry system model used for the flight test.

1.4 Players

1.4.1 DoD Test Range: This community encompasses the personnel and resources responsible for the design, execution, and report of flight test projects conducted within the DoD Design Test and Evaluation (DT&E) and Operational Test and Evaluation (OT&E) areas of responsibility. The test range community includes all government and military organizations involved with the test and evaluation of military

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[1] In practice it was possible to achieve between 98.9 - 99.99 channel utilization.

aircraft and/or their weapons systems, avionics, navigation, or the software used by these systems.

1.4.2 ARTM JPO: The ARTM Joint Program Office (ARTM JPO), located at Edwards AFB, was created to develop, test, and evaluate technology that improves the efficiency, quality, and utility of aeronautical telemetry. The ARTM team works closely with the Range Commander's Council, which represents all DoD test ranges, to keep the test community apprised of its findings. The technology developed by ARTM will be used at 18 different Air Force, Army, and Navy ranges.

1.4.3 Test Pilot School: The flight test was conducted by the NEED INFO test team, United States Air Force Test Pilot School (USAF TPS) Class O1A at USAF Flight Test Center (AFFTC), Edwards AFB, CA, from 5-31 October, 2001. The Responsible Test Organization (RTO) was the 412th Test Wing, Edwards AFB, CA.

1.5 Objectives

The results of the CCSDS evaluation are evaluated in three ways: maximum throughput (e.g., for "video data"), maximum data quality (e.g., for "memory data"), and achieve the best tradeoff between throughput and data quality (e.g., for missions involving both "video" and "memory" data). The results of the study will allow a test designer to make the following pre-mission decisions:

- Based on the type of data to be transmitted, what combination of source packet length, transfer frame length, and Reed-Solomon encoding will maximize effective throughput?

- Based on the type of data to be transmitted, what combination of source packet length, transfer frame length, and Reed-Solomon encoding will maximize the quality of the received data?
- Based on the type of data to be transmitted, what combination of source packet length, transfer frame length, and Reed-Solomon encoding will give the best tradeoff between effective throughput and data quality?

1.6 Document Organization

Chapter II establishes the background knowledge needed to understand the CCSDS packet telemetry protocol. In addition, this chapter lays the foundation for modeling the channel error-rate characteristics at Edwards AFB and discusses the results of previous efforts in packet telemetry. Chapter III outlines the methodology to be followed in developing the computer telemetry model in OPNET. Specifically, this chapter discusses the experimental factors (source packet length, transfer frame length, and Reed-Solomon encoding) and the two measures of performance (effective data throughput and data quality). It also discusses simulation length, model verification, and model validation. Chapter IV details the experimental results obtained from the methodology followed in Chapter III. Chapter V summarizes the findings indicated in Chapter IV and presents some recommendations for future study. Chapter VI summarizes the results of the flight test conducted at Edwards AFB to validate the results of the computer simulation. Finally, Chapter VII offers some overall conclusions and recommendations from the entire research effort. Details of the construction and operation of the OPNET model are given in Appendices A - D. Appendices E and F list the simulation and flight test results, respectively, in their entirety. Finally Appendix G provides a list of acronyms used throughout this report.

CHAPTER II - LITERATURE REVIEW

2.1 Introduction

The use of the CCSDS packet telemetry protocol in the test range environment will be a significant upgrade to the nearly 40-year-old technology used presently. This chapter investigates the telemetry downlink process and looks at how CCSDS fits naturally into this scheme. A detailed description of the CCSDS protocol is provided, as well as a look into previous work done in the area of packet protocol performance.

2.2 CCSDS Packet Telemetry Scheme

The purpose of a telemetry system is to reliably and transparently convey measurement information from a remotely-located data-generating source to users located in space or on Earth. Packet telemetry represents an evolutionary step from the traditional Time-Division Multiplex method of transmitting data from aircraft sources to users on the ground. As stated in the *CCSDS 100.0-G-1 Green Book* [6], the Packet Telemetry process involves the following two steps:

- Encapsulating, at the source, observational data, thus forming an autonomous packet of information in real-time on the aircraft, and
- Providing a standardized mechanism whereby autonomous packets from multiple data sources on the aircraft can be inserted into a common frame structure for transfer to the ground through noisy data channels, and delivered to facilities where the packets may be extracted for delivery to the user.

2.1.1 Data Organized Into Source Packets. Data to be transmitted between sender and receiver is organized into ***source packets***. Each packet consists of a 48-bit header and variable length data field. It is the responsibility of the application producing the data to optimize the size and structure of the data set with only a few restrictions. A source packet must consist of at least seven and no more than 65,542 bytes, allowing for data of one to 65,536 bytes. ***Idle data*** may be inserted when a packet is created with insufficient data to completely fill the source packet data field, or when a source packet must be produced in order to maintain the continuous channel data rate. A packet containing only idle data is referred to as an ***idle packet***. A diagram of the source packet structure is given in Figure 2.

<--------------------------------Primary Header						--->	<------ Data Field ------->	
Version No.	Packet Identification			Packet Sequence Control		Packet Data Length	Packet Secondary Header *	Source Data
	Type Indicator	Pckt. Sec. Hdr. Flag	Application Process Identifier	Grouping Flags	Source Sequence Count			
000	0	"1" if Sec. Hdr. present, else "0"		01 - first Pckt. 00 - cont. Pckt. 10 - last Pckt. of group 11 - no Grouping		# of bytes of packet data field minus 1		
3 bits	1 bit	1 bit	11 bits	2 bits	14 bits	16 bits	variable	variable
<----------------- 2 Octets			---------------------------->	<---------- 2 Octets ----------->		<- 2 Octets ->	<-- 1 to 65,536 Octets -->	

* optional

Figure 2. Source Packet Format [4]

The ***packet primary header*** is mandatory and consists of the following four fields: version number (3 bits), packet identification (13 bits), packet sequence control (16 bits), and packet data length (16 bits). The ***version number*** field is reserved for the possible creation of other data structures in the future. As such, version number is set to "000" to identify the data unit as a source packet. The ***packet identification*** bits are used to identify the type of packet (1 bit, set to "0" to indicate telemetry data units), indicate whether or not a packet includes a secondary header (1 bit, set to "1" if secondary header is present), and provide information on the source of the data (11 bits). Identification of the data source (i.e., application process) is tailored to local mission needs and is therefore assigned by mission management. The secondary header is mandatory if no source data field is present; otherwise it is optional. This optional header provides a means for placing ancillary data (time, internal data field format, spacecraft position/altitude, etc.) within a source packet. Use of the optional header is mission specific. The bytes making up the optional header, as determined in [4], are taken from the total possible data field bytes (i.e., if the maximum possible data field size was 65,536 bytes, the inclusion of a six byte optional header would reduce the maximum possible data field size to 65,530 bytes). The ***packet sequence control*** bits provide a sequential count of packets generated with the same application process identifier. It also includes an optional ***grouping*** feature which, when applied, provides information on the position of a source packet within a group of packets. Grouping flags make up 2 bits of the packet sequence control field, and the source sequence count is 14 bits. The source sequence count is a sequential binary count (modulo 16384). It is normally used in conjunction with a ***time code*** in the secondary header[2]. The 16-bit ***packet data length*** field contains a binary number equal to the number of bytes in the packet data field minus one. The value ranges from 0 to 65,535 bytes.

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[2] Time codes consist of an optional P-Field (Preamble Field), which identifies the time code and its characteristics, and a mandatory T-Field (Time Field). Examples of time codes are CCSDS Unsegmented Time Code and CCSDS Day Segmented Time Code. Examples of characteristics are ambiguity period, epoch, length, and resolution [4].

2.1.2 Source Packets Combine To Form Transfer Frames. Multiple asynchronous application processes on-board an aircraft generate variable-length source packets at different rates. These source packets are then multiplexed together into a synchronous stream of fixed-length *transfer frames* for reliable transmission to the ground [4]. Specifically, the transfer frame is the data structure used to transmit source packets, idle data, and privately-defined data[3] over the telemetry downlink. A transfer frame consists of the following elements: primary header (mandatory - 48 bits), secondary header (optional - up to 512 bits), data field (mandatory - variable length), operational control field (optional - 32 bits), and a frame error control field (mandatory if Reed-Solomon Encoding is not applied, otherwise optional, 16 bits). Frame length is constant throughout the period of data transmission. The *Telemetry Channel Code Green Book* [6] issued in 1987 limited the frame length to 8920 bits.

All transfer frames with the same transfer frame version number (described below) and the same aircraft[4] identifier (described in [4]) on the same physical channel constitute a ***master channel***. In most cases, the master channel will be identical to the physical channel. If, however, the physical channel also carries transfer frames with other aircraft identifiers, a distinction between master channel and physical channel is necessary [4]. A master channel is composed of up to eight ***virtual channels***. The use of virtual channels allows multiple packet-producing sources to effectively be granted exclusive access to a physical channel by assigning them transmission capacity on a frame-by-frame basis. Each transfer frame belongs to one of the up to eight virtual

[3] Privately defined data is specialized high-rate data or other data not suitable for CCSDS source packet structuring [4].
[4] The CCSDS information has been modified by using the term "aircraft" in place of "spacecraft" in order to more directly apply the CCSDS recommendation to the flight test application.

channels on one master channel. Once created, virtual channels exist until changed/deleted by the user. The virtual channels are constant during the period of data transmission.

Figure 3 illustrates the transfer frame format. The 48-bit transfer frame primary header consists of the following five fields: version number (2 bits), frame identification (14 bits), master channel frame count (8 bits), virtual channel frame count (8 bits), and data field status (16 bits). The ***version number*** bits are set to "00" to identify the data unit as a transfer frame. The ***frame identification*** field is further divided into an aircraft identifier (10 bits), virtual channel identifier (3 bits), and an operational control field flag (1 bit). This field identifies the source of the transfer frame, specifies which virtual channel the frame belongs to, and provides information on the format of the frame. A more complete description of these three sub-fields can be found in the *CCSDS Packet Telemetry Blue Book* [4]. The ***master channel frame count*** is a sequential binary count (modulo 256) of each transfer frame transmitted in a particular master channel. Similarly, the ***virtual channel frame count*** is a sequential binary count (modulo 256) of each transfer frame transmitted in a particular virtual channel of a master channel. The purpose of the master channel frame count is to provide a running count of the frames transmitted through the same master channel. The virtual channel frame count provides individual accountability for each of the virtual channels (maximum of eight). The 16 ***data field status*** bits are further divided into a secondary header flag (1 bit), synchronization flag (1 bit), packet order flag (1 bit), segment length identifier (2 bits),

<------ Transfer Frame Primary Header ------>											<----- Transfer Frame Secondary Header (optional) ----->			Transfer Frame <-- Data -> Field	Operational Control Field (opt)	Frame Error Control Field (opt)[5]
Transfer Frame Version No.	Transfer Frame Identification			Master Channel Frame Count	Virtual Channel Frame Count	Transfer Frame Data Field Status					Transfer Frame Secondary Header ID		Transfer Frame Second. Header Data	Aircraft Application Data	Operational Control Field Data	Frame Error Control Field Data
	Aircraft ID	Virtual Channel ID	Oper. Control Field Flag			Transfer Frame Second. Header Flag	Synch. Flag	Packet Order Flag	Segment Length ID	First Header Pointer	Transfer Frame Second. Header Version No.	Transfer Frame Second. Header Length				
00											00					
2 bits	10 bits	3 bits	1 bit	8 bits	8 bits	1 bit	1 bit	1 bit	2 bits	11 bits	2 bits	6 bits	max 504 bit	max 1107 bytes	32 bits	16 bits

Figure 3. Transfer Frame Format (derived from [4])

[5] If Reed-Solomon encoding is not used, the 2-byte frame-error control field must be used. If Reed-Solomon encoding is used, 160 check bytes are appended to the transfer frame and the frame-error control field is not used.

and first header pointer (11 bits). Again, a more complete description of these sub-fields can be found in the *CCSDS Packet Telemetry Blue Book* [4].

If present, the transfer frame ***secondary header*** is used to carry fixed-length mission-specific data. It consists of an identification field (8 bits) and a data field (up to 504 bits). The secondary header is associated with either a master or virtual channel.

The transfer frame data field is used to carry the data to be transmitted. It can vary in length from one to 1107 bytes. This number is reduced if the optional transfer frame header fields are used.

The optional ***operational control field*** is used to provide the status of telecommand or other aircraft operations activities. If present, this field will occur in every transfer frame transmitted through either a master or virtual channel throughout the mission phase.

The purpose of the 2-byte ***frame error control field*** is to detect any errors introduced into the frame during the transmission and data handling process. If this optional field is present, it will occur in every transfer frame transmitted within the same master channel throughout the mission phase.

2.1.3 Telemetry Data Flow. Figure 4 illustrates data flow in the CCSDS packet telemetry scheme. At the top of the diagram, multiple on-board data sources are producing source packets. These source packets are then multiplexed into transfer frames of several virtual channels. The transfer frames are subsequently transmitted to the ground over the physical channel using appropriate synchronization techniques. The use of virtual channels allows the data to be organized by data type, prioritized according to mission requirements, or separated according to source and destination.

The specific role the virtual channels will play is outside the scope of this research and does not affect its results. More information on intelligent selection of data streams to reduce required telemetry downlink bandwidth is in [19]. For this research, it is assumed that multiple data sources are represented by one collective data source producing source packets into a single virtual channel. These source packets are then organized into transfer frames on a first-come-first-serve basis and transmitted over the physical channel to the ground. On the ground the process is reversed; the transfer frames are disassembled into the original source packets, which are then delivered to one or more sink processes. Figure 5 shows the packet telemetry scheme redrawn to reflect the telemetry flow model used in this research. For this investigation, performance measurements were taken starting from the point the source packets are generated to the point where the transfer frames arrive on the ground and the source packets are reconstructed. Processing time on the ground is application-dependent and therefore not taken into account.

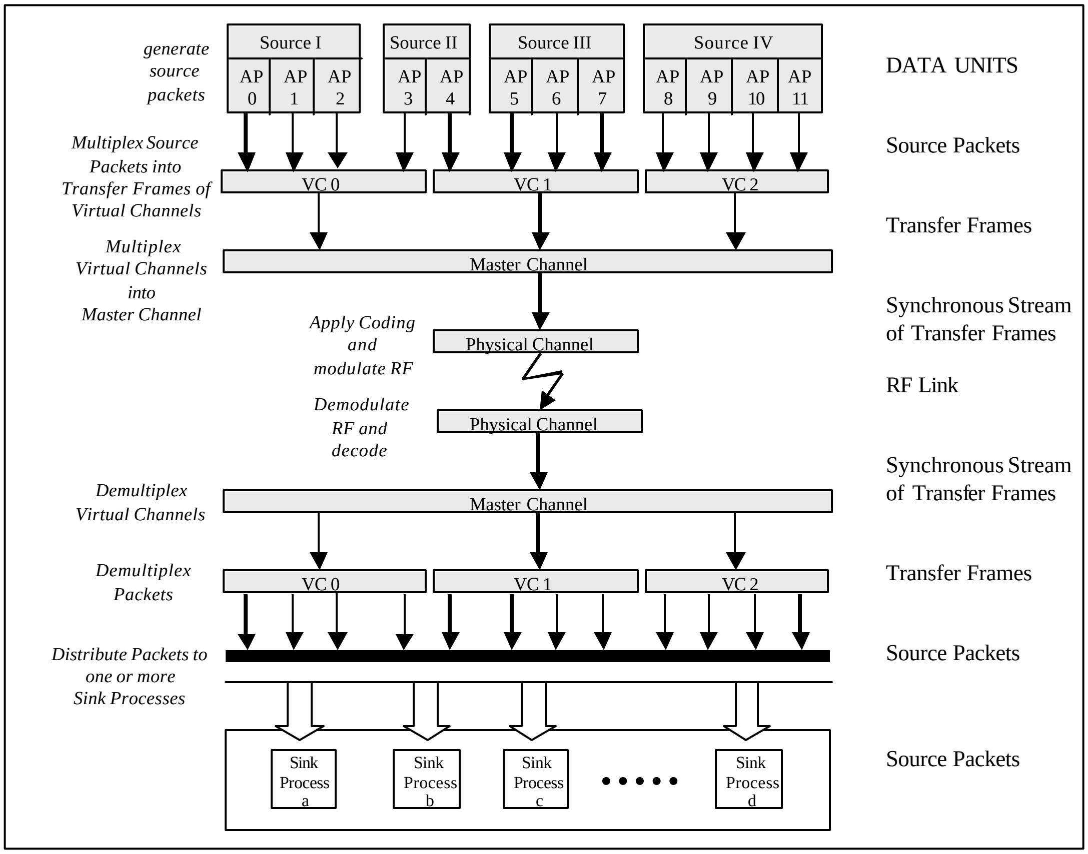


Figure 4. Telemetry Data Flow [2]

2.3 Channel Characterization

The performance of any telemetry downlink scheme is heavily influenced by the bit error characteristics of the physical channel. The dominant source of bit errors and short term link failures at Edwards AFB are "clusters" of severe error burst activity caused by fading, poor antenna patterns, multipath interference, or shadowing [18, 20]. The bit error rate (BER) of the typical 1-20 Mb/sec RF link can vary from a relatively clean 10^{-12} to an essentially unusable 0.5. The experimental model must, therefore, incorporate channel characterization in order to accurately determine the effective performance of a data transfer.

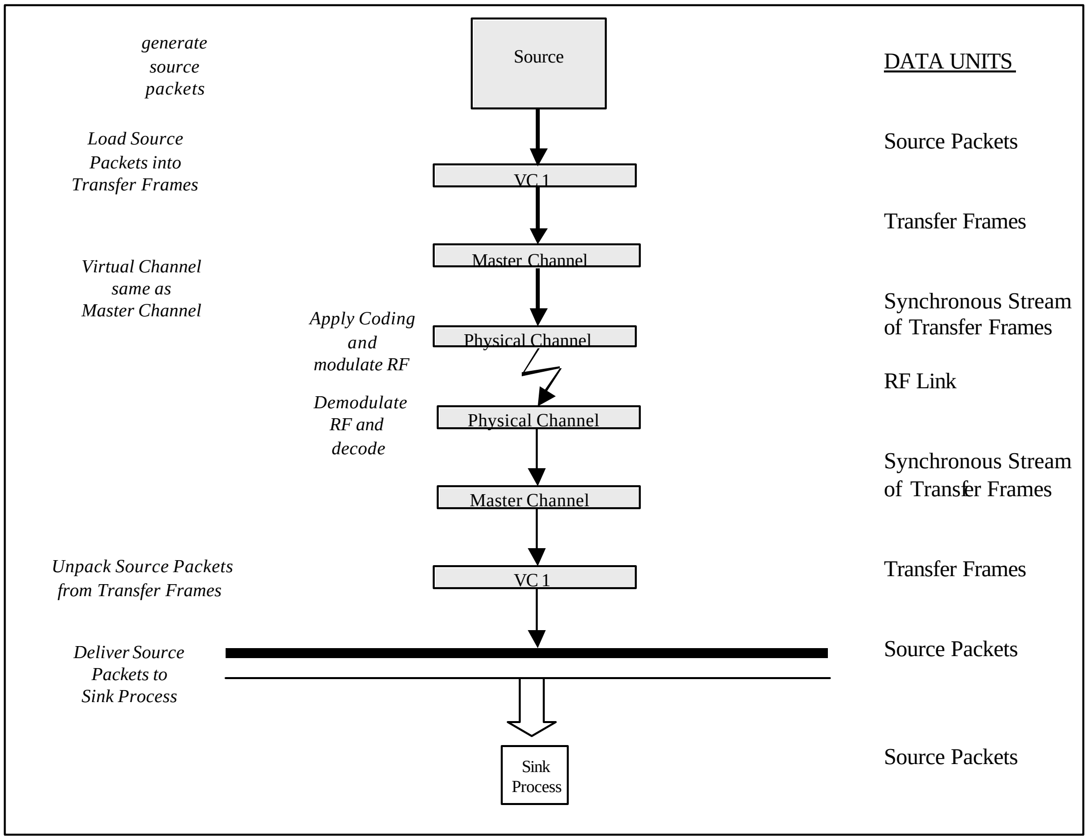


Figure 5. Telemetry Data Flow Used In Research Work

Both [18, 20] investigate link availability and burst error analysis at Edwards AFB. Their results indicate that the channel errors occur in bursts, rather than randomly, and are due to multipath interference which occurs at seemingly random intervals. To accurately represent the bit error activity, real-time bit error activity sampled from the Edwards AFB test range were incorporated into the OPNET simulation model.

2.4 Modeling of the Telemetry Downlink

The telemetry downlink can be modeled as a point-to-point communication system using a two-layer protocol architecture. The communication system consists of two nodes in a simplex environment. Communication is from the airborne node to the ground node with no data retransmission or data acknowledge capabilities. Multiple users (on-board data sources) use the sender (airborne) node to transmit data messages to the receiver (ground) node. The modified two-layer protocol model is shown in Figure 6.

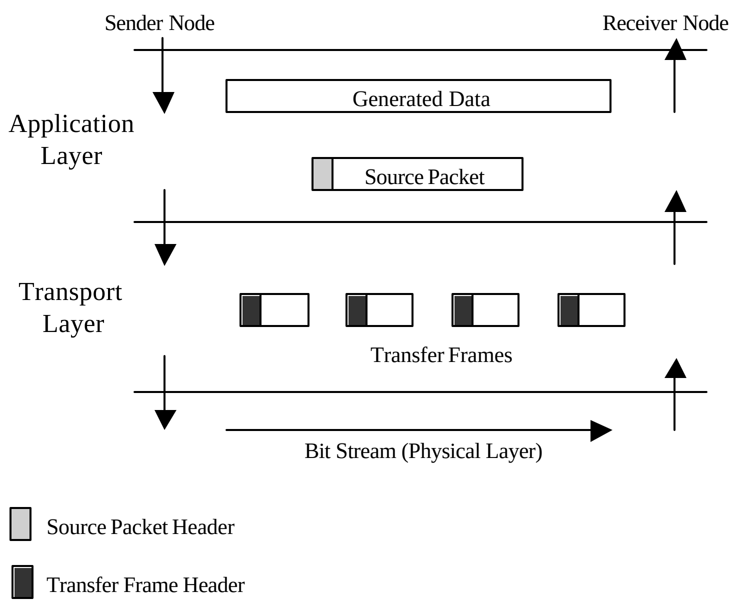


Figure 6. Two-Layer Protocol Architecture [7]

This model is analogous to the application and transport layers in the OSI reference model. Generated data is split into source packets by each on-board data source, and protocol control information (PCI), namely the 48-bit source packet header, is prepended in the application layer. At the transport layer, source packets are segmented into transfer frames and another 48-bit header is added to each. Since queuing and processing at each layer contributes to the overall transmission delay, the system could be analyzed using a multi-queue model instead of a single queue as was done in [11]. However, since the basis of performance measurements is the entry of source packets into the virtual channel, the architecture simulated in OPNET consists of only the transport layer and is, therefore, modeled as a single queue. Delays due to segmentation of data into source packets and the assembly of source packets into transfer frames are a function of the speed of the computer equipment and are assumed to be negligible compared to the transmission delay, which is estimated at 1.75e-05 seconds (c.f., Appendix A). All transfer frames follow the same path, hence they arrive at the destination node in the same order they left the source node. Using standard queuing notation, the system can be modeled as shown in Figure 7.

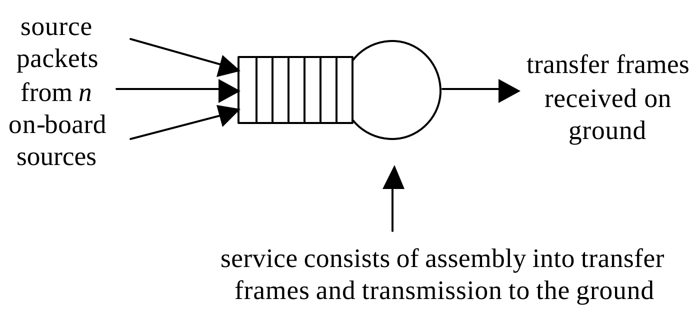


Figure 7. Queuing Model

2.5 Reed-Solomon Encoding

The Reed-Solomon code is a powerful burst error correcting code with an extremely low undetected error rate [6]. The code contained in the CCSDS recommendation is a (255, 223) Reed-Solomon code, meaning that 225 output bytes result from an encoding of 223 input bytes. This will be described in more detail shortly. The code is a non-binary code. Each member of its coding alphabet is one of 256 elements of a finite field rather than zero or one. A string of eight bits is used to represent elements in a field so that the output of the encoder still looks like binary data. The Reed-Solomon code is also systematic. This means that some portion of the codeword contains the input data in unalterable form. In this case, the first 223 bytes are the unaltered input data followed by 32 check bytes. This (255, 223) code is capable of correcting up to 16 byte errors in each codeword.

In addition, the Reed-Solomon codewords can be byte interleaved. This separates bytes in a codeword making it less likely that burst errors disturb more than one byte in any codeword, thus improving the performance of the code. An interleaving depth of five was chosen by the Consultative Committee for Space Data Systems because it results in performance that is virtually indistinguishable from a depth of infinity. Further, a depth of five results in a codeblock (one codeblock equals a set of five codewords plus the check symbol field) which is a good compromise considering ease of handling, data outages and frame synchronization rate. Defined in this manner, a codeblock is synonymous with a transfer frame.

The following summarizes the use of Reed-Solomon encoding in the CCSDS recommendation:

One RS codeword = 223 data bytes + 32 check bytes

With the interleave set to five,

One RS codeblock = 5 x (One RS codeword)
= 5 x (223 data bytes + 32 check bytes)
= 1115 data bytes + 160 check bytes

A transfer frame is synonymous with a codeblock, therefore a transfer frame (with Reed-Solomon turned ON) consists of up to 1115 bytes (includes header information) and 160 bytes of error detection/correction information.

The same encoding and decoding hardware can also implement a shortened version of the codeblock. This is accomplished by assuming the remaining bytes are fixed, in this case they are assumed to be all zero. This virtual zero fill allows the transfer frame length to be tailored to suit a particular mission. In short this means that the transfer frame length can be less than 1115 bytes. All 160 check bytes are still required, however, regardless of the payload length.

If Reed-Solomon is turned OFF, the 160 bytes of check data are replaced with two CRC bytes and four bytes are appended to each transfer frame (regardless of whether Reed-Solomon is ON/OFF) for the purpose of frame synchronization. The following two transfer frame configurations are possible:

- No Reed-Solomon:

$$\underbrace{\text{synchronization}}_{\text{4 bytes}} + \underbrace{\text{transfer frame}}_{\text{8-byte header + up to 1107 bytes of data}}$$

- With Reed-Solomon:

$$\underbrace{\text{synchronization}}_{\text{4 bytes}} + \underbrace{\text{transfer frame}}_{\text{6-byte header + up to 1109 bytes of data}} + \underbrace{\text{R-S check symbols}}_{\text{160 bytes}}$$

2.6 Previous Work In This Area

A 1998 study by Chen, Kimura, and Ebihara [11] looked at optimal packet length to minimize mean data transmission delay in a point-to-point communication system for both two-layer and three-layer protocol structures. Their two-layer model consisted of a network and data link control (DLC) layer, with retransmission occurring at the network layer. Their model used two M/M/1 queues with Poisson-distributed data arrival and exponentially-distributed service times at each module. Packet segmentation and reassembly delays were ignored. They found optimal packet length depended on only the mean packet length, average BER, and the protocol control information (PCI) length of the network layer. This relationship is shown in Equation (1). Here, packets are analogous to CCSDS transfer frames, and PCI length analogous to CCSDS source packet length.

Optimal packet length, x_{OPL}, is

$$x_{\mathrm{OPL}} = \min\left(L, -\frac{1}{\ln(1-p_e)}\right) + h_2 \qquad (1)$$

where, L is the average packet length in bits, p_e is the average BER, and h_2 is the PCI length of the network layer in bits.

The study concludes that optimal packet length is most affected by the BER of the transmission media and the mean packet length. Efficiency and throughput of data transmission was better as the packet length increased. This study did not investigate burst error conditions. Although the model used in [11] is not identical to that used here (the use of M/M/1 queues does not apply in the telemetry model and the RF channel errors are very bursty in nature), it is reasonable to predict similar results; specifically that BER and source packet length have a strong effect on the recommended transfer frame length, and that throughput tends to increase as transfer frame length increases.

Unlike [11], a 1996 study by Hara, Ogino, Araki, Okada, and Morinaga [22] specifically examined radio communication system performance in the presence of burst errors in a Rayleigh channel. They proposed an efficient stop-and-wait automatic repeat request (SAW-ARQ) protocol with adaptive packet length to provide reliable mobile data packet transmission. The SAW-ARQ protocol controls the transmitting packet length according to the time-varying channel condition estimated by the number of ACKs (acknowledgement packets) and NACKs (negative-acknowledgment packets). As in [11], this study showed a strong correlation between channel bit error and optimal packet length. Unlike the telemetry model in this project, the SAW-ARQ study was able to adjust packet length dynamically through the use of control messages (i.e., ACKs and

NACKs) from the receiving node. The duplex-nature of their model is a luxury not currently afforded in the simplex telemetry downlink model. Nonetheless, the results of this study again indicate the necessity of accurately modeling the RF channel in the OPNET simulation.

A 1979 study by Minoli [7] found the optimal packet length to meet end-to-end delivery delay requirements in a single link packet voice communication. As in the other studies, this study highlights the basic tradeoff between longer packets, which increase throughput and decrease overhead percentages, and shorter packets, which increase data quality (thus reducing the number of retransmissions due to bit error). Minoli also organized packet length results based on typical operating conditions into a table format. Given channel capacity, amount of packet overhead (in bits), and the digitization rate, the user is presented with the proper packet length to meet pre-established end-to-end delivery requirements.

2.7 Summary

The CCSDS packet telemetry protocol represents a promising technology for the DoD test range community. Research and evaluation of telemetry systems, and in particular the CCSDS protocol, is on-going at Edwards AFB and elsewhere. This chapter has reviewed some of the primary concepts of the telemetry downlink and described the inner workings of the CCSDS protocol. The next chapter will lay the foundation for evaluating and optimizing the use of CCSDS in the test range environment to satisfy mission requirements.

CHAPTER III - METHODOLOGY

3.1 Introduction

This chapter discusses the approach taken to predict the performance of the CCSDS protocol in the test range environment. The factors affecting protocol performance are first discussed and simplifying assumptions made to facilitate construction of the computer model used to simulate the downlink of telemetry data at Edwards AFB. Next, the critical CCSDS parameters, transfer frame size, source packet length, and Reed-Solomon encoding, are discussed along with the primary measures of performance used to evaluate protocol performance, throughput and data quality. Finally, two issues fundamental to the construction and use of the computer model, namely simulation length and characterization of the channel error, are introduced.

3.2 Description of Experiments

3.2.1 System Definition. The goal of this investigation is to evaluate the performance of the CCSDS packet telemetry standard in the DoD test range environment. The system consists of two nodes, an airborne node and a ground node. The airborne node generates source packets, constructs transfer frames from the source packets, and transmits the transfer frames to the ground. The ground node receives the transmitted transfer frames, unpacks the source packets, and delivers the source packets to the appropriate end users. Source packets may be bigger or smaller than a single transfer frame. The system under investigation includes all the components in the telemetry downlink process, from the point the source packets arrive to be loaded into the transfer frames, to the point the transfer frames arrive at the ground node and the source packets are reformed. This methodology is designed so that the effects of components outside the defined system were minimized. The evaluation was performed using the OPNET network modeling software. The results of the software simulations were later validated by flight test. A description of the OPNET model is in Appendices A and B.

3.2.2 Experimental Parameters

The parameters that affect the performance of the system include the following:

- Error correction encoding
- Source packet length
- Transfer frame length
- Channel BER
- Source packet generation rate
- Percentage of filler data in transfer frames
- Number of on-board data sources
- Speed of PCM equipment
- Aircraft altitude
- Antenna pattern on aircraft
- Weather
- Test range location (i.e., Edwards AFB versus Nellis AFB)
- Data rate of RF downlink (1-20 Mbps)
- Source packet overhead
- Transfer frame overhead

3.2.3 Experimental Factors

The key factors chosen for this investigation were the following:

- Error correction encoding
- Source packet length
- Transfer frame length

The factors were chosen based on resource availability and usefulness of the results to the sponsors. Each will be discussed in further detail. The remaining parameters were not chosen as factors for the following reasons.

- Bit error rate: Flight tests conducted by the ARTM project office have confirmed the two primary sources of bit errors and short-term failure links in the traditional test corridors at Edwards AFB are "error bursts" and "error clusters". A characterization of these channel errors is given in Appendix A. A custom link model was built in OPNET to simulate the channel and was used during all simulation runs.

- Source Packet Generation Rate: Given the limited RF spectrum allocation, users in the test range community have a strong interest in maximizing channel usage [13]. Therefore, only those combinations of CCSDS parameters that provide near-100% channel utilization are used. This is accomplished by setting the source packet generation rate to achieve as close to 100% channel utilization as possible. Typical channel utilization rates attained were on the order of 99.9%.

- Percentage of filler data: This is directly related to source packet length and source packet generation rate and would therefore be redundant.

- Number of on-board data sources: This is related to source packet generation rate and would therefore be redundant.

- Speed of PCM equipment at source and destination: This is beyond the scope of this investigation and was assumed to be sufficient.

- Flight altitude, Antenna pattern on aircraft, Weather, and Test range location: The resources needed to directly examine these parameters were not available. Effects due to these parameters were taken into account by the channel BER.

- Data rate of RF downlink: This parameter ranges in value from 1 to 20 Mbps. For this investigation the value was held constant at 1 Mbps. This value was chosen after consultation with ARTM to pick a data rate compatible with the equipment used during the flight test. The data rate was also used during the simulations to facilitate a comparison of simulation and flight test results.

- Transfer Frame and Source packet overhead: The value of these parameters is dictated by the CCSDS standard. The purpose of this investigation is to find the most efficient use of the standard, not to alter it.

Error Correction: While the addition of error-detection bits aids in the determination of whether the data received on the ground is "good" or "bad", it also increases transmission overhead and decreases the effective throughput of "good" data. Typical "best effort" systems have classically made little use of error checking due to end users' opinion that "even bad data is better than no data [13]." The optional error-detection and correction method in the CCSDS recommendation is Reed-Solomon encoding, which is a powerful burst-error-correcting code. A detailed description of Reed-Solomon coding can be found in Chapter II. If used, an additional 160 bytes of check symbols must be appended to the transfer frame. If not used, the 2-byte frame-error control field of the transfer frame header must be used.

Source Packet Length: Data to be transmitted between sender and receiver is organized into source packets. Each packet consists of a 48-bit header and variable length data field. A source packet must consist of at least seven, and no more than 65,542, bytes. Source packets may be fixed or variable length during a mission [4, 5]. The following source packet payload lengths (in bytes) will be tested: 5, 194, 500, 2000, 20000, and 60000. These values were chosen to cover the spectrum of possible lengths. The 194-byte data point was chosen so that one source packet would exactly fit into one 200-byte transfer frame payload. These test cases produced enough sample points to get an initial view of how source packet length affects throughput and data quality. Once the experiments were underway, source packet length was more precisely set based on the preliminary performance results.

Transfer Frame Length: Source packets are multiplexed together into a synchronous stream of fixed-length transfer frames for transmission to the ground. Frame length is constant throughout a specific mission phase and is limited to 1115 bytes. For this investigation, two configurations of the transfer frame header were used. When Reed-Solomon encoding was used, the transfer frame header consisted of only the 6-byte primary header. In this case, an additional 160 bytes (Reed-Solomon check symbols) was appended to the transfer frame. When Reed-Solomon encoding was not used, an 8-byte transfer frame header was used (6-byte primary header plus 2-byte frame error control field). Regardless of transfer frame length, a 4-byte synchronization pattern was appended to the beginning of the transfer frame. This synchronization marker was used by the receiving network to acquire synchronization with the frame boundaries after transmission through the data channel. The two transmission configurations used are:

- No Reed-Solomon:

  synchronization + transfer frame

  4 bytes — 8-byte header + up to 1107 bytes of data

- With Reed-Solomon:

  synchronization + transfer frame + R-S check symbols

  4 bytes — 6-byte header + up to 1109 bytes of data — 160 bytes

The following transfer frame payload lengths (in bytes) were tested: 41, 200, 400, 600, 800, and 1000. These values were chosen to cover the spectrum of possible transfer frame payload lengths. The payload length of 41 bytes was chosen so that the total transmitted block of 53 bytes (data + 6-byte transfer frame header + 2 CRC bytes + 4 synchronization bytes) would mirror a 53-byte ATM cell. This was done to aid in the application of these research results to an ATM-based packet telemetry scheme.[6] These test cases produced enough sample points to get an initial view of how transfer frame

[6] This 'ATM test case' does not apply when Reed-Solomon encoding is used because the minimum number of bytes in a transmitted block is 171 (4 sync bytes + 7 byte transfer frame + 160 bytes R-S check symbols).

length affects throughput and reliability. Once the experiments were underway, transfer frame length was more precisely set based on the preliminary performance results.

3.2.4 Performance Metrics. The performance metrics used in this investigation are defined as follows:

Effective Data Throughput: The average number of data bytes successfully received by the ground node per unit time, in bytes per second. A byte was considered successfully received if it was part of a transfer frame that was successfully received. A transfer frame was successfully received if the number of bytes in error was within allowable tolerances. The error tolerances depended on whether Reed-Solomon encoding was being used or not. If Reed-Solomon encoding was not used, a transfer frame was considered successfully received if no byte errors were detected by the frame-error control bytes. Effective data throughput was computed by dividing the number of data bytes received by the time (in seconds) it took to transmit the data bytes plus the associated overhead.

Data Quality: The percentage of successfully received source packets at the ground node. This statistic was expressed as a percentage, with 100 indicating error-free data transmission. This metric was computed by dividing the number of source packets successfully received at the ground node by the total number of source packets transmitted.

Channel Utilization: A measure of the consumption of the available RF channel bandwidth. It measured the proportion of the transmitted data stream containing actual telemetry information (data + overhead), versus "idle" data used to complete an unfilled transfer frame. This statistic was expressed as a percentage, with 100 indicating full usage. The source packet generation rate was set in each case to achieve near-100% channel utilization. This parameter was measured for the purpose of model verification and not to optimize CCSDS performance.

Data Latency: The period between when the source packet was generated and when it was received in its entirety on the ground, measured in seconds. This metric was not used to optimize CCSDS performance, instead it was observed during each simulation run for the purposes of model verification.

3.2.5 Protocol Optimization. The results of the simulations were evaluated in three ways: for maximum throughput (e.g., for "video data"), maximum data quality (e.g., for "memory data"), and to achieve the best tradeoff between throughput and data quality (e.g., for missions involving both "video" and "memory" data). The results of the study will allow a test designer to make the following pre-mission decisions:

- Based on the type of data to be transmitted, what combination of source packet length, transfer frame length, and Reed-Solomon encoding will maximize effective throughput?

- Based on the type of data to be transmitted, what combination of source packet length, transfer frame length, and Reed-Solomon encoding will maximize the reliability of the received data?
- Based on the type of data to be transmitted, what combination of source packet length, transfer frame length, and Reed-Solomon encoding will give the best tradeoff between effective throughput and data quality?

Table 1 lists the experimental factors that were varied in the course of the study. Each factor could take on a finite set of values, referred to as levels.

Table 1. Experimental Factors

Factor	# of Levels	Levels
Source Packet Length	6	5, 194, 500, 2000, 20000, 60000 bytes
Transfer Frame Length	6	41, 200, 400, 600, 800, 1000 bytes
Error Correction	2	R-S or no R-S

The number of experiments required for a full factorial evaluation was 6x6x2 = 72. These were used for the initial study (with five replications). After the preliminary trends were discovered, the experiments were more finely focused to key in on areas of interest and usefulness. Table 2 summarizes the experiment schedule. After the initial 72 simulation runs, certain ranges of transfer frame and source packet lengths were "zoomed in" upon to increase the precision with which values were chosen to maximize throughput and/or data quality.

The final data run in the initial set, number 73, was added to compare the performance of the CCSDS and ATM protocols. Given the individual header/overhead requirements of the ATM and CCSDS protocols, it was not possible to configure a

CCSDS transfer frame, and/or source packet, to have 48 bytes of useful data and five bytes of overhead as exists in an ATM cell. With this "simple" solution not available, the next best solution was to conduct the ATM/CCSDS performance comparison using a CCSDS transfer frame-source packet combination of the same data-to-overhead ratio as an ATM cell, namely 48:5. The result was a transfer frame payload length of 179 bytes and a source packet payload length of 173 bytes. Derivation of these values is shown in Appendix C.

3.3 Determining Simulation Length & Sample Size

Using a typical T-39 mission length of three hours, each of the 73 simulations could have been run for up to three hours, in simulation time (vice wall clock), and the resulting performance data (e.g., throughput and data quality) collected. This approach, however, would needlessly waste time and resources since the same performance information could be attained in less than three hours. The simulation length used was based on the desired level of accuracy and confidence. Based on the notion that this batch of simulations was only the first wide-sweeping look at where maximum performance might occur, a desired accuracy of 90% and a confidence level of 80% were chosen. Simulation length calculations are shown in Appendix E. Each simulation was executed five times, using different random number generator seeds. This sample size resulted in a worst-case confidence level of 90%. Throughput data from these simulations is accurate within ±180 Bps, and data quality data is accurate within ±0.15 percentage points. Confidence and accuracy calculations are shown in Appendix E.

Table 2. Experiment Descriptions

Run	TF Len (bytes)	SP Len (bytes)	RS	SP Data Rate (Bps)
1	41	7	N	92865
2	41	200	N	95910
3	41	500	N	96390
4	41	2000	N	96620
5	41	20000	N	96690
6	41	60000	N	96700
7	200	7	N	116720
8	200	200	N	116720
9	200	500	N	117520
10	200	2000	N	117800
11	200	20000	N	117910
12	200	60000	N	117920
13	400	7	N	120720
14	400	200	N	120720
15	400	500	N	121040
16	400	2000	N	121230
17	400	20000	N	121350
18	400	60000	N	121350
19	600	7	N	122110
20	600	200	N	122110
21	600	500	N	122110
22	600	2000	N	122440
23	600	20000	N	122540
24	600	60000	N	122540
25	800	7	N	122820
26	800	200	N	122820
27	800	500	N	122820
28	800	2000	N	123040
29	800	20000	N	123140
30	800	60000	N	123150
31	1000	7	N	123250
32	1000	200	N	123250
33	1000	500	N	123250
34	1000	2000	N	123380
35	1000	20000	N	123500
36	1000	60000	N	123510

Run	TF Len (bytes)	SP Len (bytes)	RS	SP Data Rate (Bps)
37	41	7	Y	60160
38	41	200	Y	61425
39	41	500	Y	61620
40	41	2000	Y	61715
41	41	20000	Y	61745
42	41	60000	Y	61745
43	200	7	Y	102380
44	200	200	Y	102380
45	200	500	Y	103000
46	200	2000	Y	103210
47	200	20000	Y	103300
48	200	60000	Y	103300
49	400	7	Y	105000
50	400	200	Y	105000
51	400	500	Y	105240
52	400	2000	Y	105390
53	400	20000	Y	105480
54	400	60000	Y	105480
55	600	7	Y	105900
56	600	200	Y	105900
57	600	500	Y	105900
58	600	2000	Y	106150
59	600	20000	Y	106220
60	600	60000	Y	106230
61	800	7	Y	106360
62	800	200	Y	106360
63	800	500	Y	106360
64	800	2000	Y	106530
65	800	20000	Y	106600
66	800	60000	Y	106610
67	1000	7	Y	106640
68	1000	200	Y	106640
69	1000	500	Y	106640
70	1000	2000	Y	106740
71	1000	20000	Y	106830
72	1000	60000	Y	106830
73	179	173	N	115820

TF Len = transfer frame payload length in bytes; SP Len = source packet payload length in bytes; RS = Reed-Solomon (N = off, Y = on); SP Data Rate = source packet generation rate in bytes per second (based on 100% channel utilization)

During the effort to determine a suitable simulation length, it became clear that no one length would satisfy the accuracy and confidence level requirements in all 73 cases. As a result, simulation length calculations were performed for all 73 cases. There were distinct groupings among the simulation lengths calculated, falling out primarily by source packet length. To simplify execution of the simulations, four simulation lengths were chosen according to these groupings. The simulation schedule is repeated in Table 3 with the simulation length for each case shown. Each simulation was run for the simulation length that achieved the desired accuracy and confidence level or for three hours, whichever number was smaller. In all cases, the channel error characteristics were the same, namely 88% of the time the channel was "error free", 10% of the time the channel experienced "cluster" errors, and 2% of the time it experienced "burst" errors.

3.4 Channel Characterization

To emulate the bursty-error behavior of the downlink channel, a custom-designed link model was used (Appendix A contains a complete description). Numerous efforts have been made to measure bit error performance of aeronautical telemetry links [18]. Fusing channel characterization results and demodulated bit error probability (BEP) files into systematic conclusions is highly problematic since there is no single air-to-ground channel scenario. Flight profile, vehicle speed ranges, antenna type and placement, and local terrain are all uncontrolled variables that significantly influence channel characteristics.

Table 3. Experiment Schedule Including Simulation Length

Run	TF Len (bytes)	SP Len (bytes)	RS	SP Data Rate (Bps)	Sim Length (sec)	Run	TF Len (bytes)	SP Len (bytes)	RS	SP Data Rate (Bps)	Sim Length (sec)
1	41	7	N	92865	35	37	41	7	Y	60160	35
2	41	200	N	95910	35	38	41	200	Y	61425	35
3	41	500	N	96390	35	39	41	500	Y	61620	35
4	41	2000	N	96620	35	40	41	2000	Y	61715	35
5	41	20000	N	96690	10800	41	41	20000	Y	61745	10800
6	41	60000	N	96700	10800	42	41	60000	Y	61745	10800
7	200	7	N	116720	35	43	200	7	Y	102380	35
8	200	200	N	116720	35	44	200	200	Y	102380	35
9	200	500	N	117520	35	45	200	500	Y	103000	35
10	200	2000	N	117800	35	46	200	2000	Y	103210	35
11	200	20000	N	117910	3300	47	200	20000	Y	103300	3300
12	200	60000	N	117920	3300	48	200	60000	Y	103300	3300
13	400	7	N	120720	35	49	400	7	Y	105000	35
14	400	200	N	120720	35	50	400	200	Y	105000	35
15	400	500	N	121040	35	51	400	500	Y	105240	35
16	400	2000	N	121230	35	52	400	2000	Y	105390	35
17	400	20000	N	121350	3300	53	400	20000	Y	105480	3300
18	400	60000	N	121350	3300	54	400	60000	Y	105480	3300
19	600	7	N	122110	35	55	600	7	Y	105900	35
20	600	200	N	122110	35	56	600	200	Y	105900	35
21	600	500	N	122110	35	57	600	500	Y	105900	35
22	600	2000	N	122440	35	58	600	2000	Y	106150	35
23	600	20000	N	122540	3300	59	600	20000	Y	106220	3300
24	600	60000	N	122540	3300	60	600	60000	Y	106230	3300
25	800	7	N	122820	35	61	800	7	Y	106360	35
26	800	200	N	122820	35	62	800	200	Y	106360	35
27	800	500	N	122820	35	63	800	500	Y	106360	35
28	800	2000	N	123040	35	64	800	2000	Y	106530	35
29	800	20000	N	123140	3300	65	800	20000	Y	106600	3300
30	800	60000	N	123150	3300	66	800	60000	Y	106610	3300
31	1000	7	N	123250	35	67	1000	7	Y	106640	35
32	1000	200	N	123250	35	68	1000	200	Y	106640	35
33	1000	500	N	123250	35	69	1000	500	Y	106640	35
34	1000	2000	N	123380	35	70	1000	2000	Y	106740	35
35	1000	20000	N	123500	750	71	1000	20000	Y	106830	750
36	1000	60000	N	123510	750	72	1000	60000	Y	106830	750
						73	179	173	N	115820	35

TF Len = transfer frame payload length in bytes; SP Len = source packet payload length in bytes; RS = Reed-Solomon (N = off, Y = on); SP Data Rate = source packet generation rate in bytes per second (based on 100% channel utilization)

Despite these difficulties, flight tests conducted by the ARTM project office have confirmed the two primary sources of bit errors and short-term failure links in the traditional test corridors[7] at Edwards AFB are "error bursts" and "error clusters". An error burst is a sporadic, impulse-type event, where the BEP suddenly degrades to the range of 10^{-3} to 10^{-5}. The duration of error bursts (at T-39 speeds over the baseline corridors) is in the range of a few hundred milliseconds (msec) to one second. The second type of error, an error cluster, occurs more frequently and is associated with strong, two-ray, frequency selective fades. They are primarily seen when the receiving antenna main lobe grazes the ground or horizon. BEP values during an error cluster are approximately 0.5. Actually, the receiver/detector has lost synchronization--the link is broken. The link model used in the OPNET design was built to emulate the real-world channel behavior as closely as possible.

From ARTM's work to characterize the telemetry link it is known that two types of errors can occur - error clusters and error bursts. Although it is difficult to precisely quantify the channel behavior, for the purposes of this research only an approximate level of accuracy was required. Table 4 summarizes the channel profile that was used. These values are based on "typical" results from ARTM flight tests.

Table 4. Channel Profile

State	Percentage of time spent in state (%)	BEP	Duration (msec)
Error-free	88	0	variable
Error-cluster	10	0.5	100-1000
Error-burst	2	10^{-5} - 10^{-3}	200

[7] The ARTM project used four of the traditional test corridors at Edwards AFB, however the most useful (repeatable) baseline link performance data was obtained from three--"CORDs Road", "Black Mountain", and one of the high altitude supersonic corridors.

3.5 Model Validation

The purpose of validating the model is to ensure the assumptions used in developing it, the input parameter values and distributions, and the output values and conclusions are reasonable in that the results are close to that observed in real systems [12]. The assumptions made in constructing this model (e.g., errors due to environmental variables, such as weather and flight altitude, can be lumped into channel BER) were validated by expert intuition, namely members of the ARTM project office. The input parameter values and error distributions (i.e., channel characterization) used representative real-world results from previous flight tests at Edwards AFB. The output values and conclusions of this investigation were validated by flight test in October 2001 as part of the USAF TPS curriculum.

3.6 Model Verification

In simple terms, the purpose of verifying the model is to ensure it does what it is intended to do. This can also be referred to as debugging. This was done by building the model in a modular fashion and running progressively more complex simulations. For example:

- constant input stream with error-free channel
- constant input stream with constant channel error-rate
- constant input stream with realistic channel error

In addition, other debugging-type checks were made, such as ensuring the number of bytes generated by the data sources equals the number of bytes received at the ground-node and monitoring data latency of the source packets for any anomalies.

3.7 Summary

This chapter has detailed the methodology to be used in evaluating the CCSDS protocol in the test range environment. While some simplifying assumptions were made, the overall channel BER should incorporate the combined errors due to the environmental variables removed by the assumptions. A complete description of the OPNET model is given in Appendices A and B. For a full factorial experiment, 72 initial test cases were run, plus one test case to compare the performance of the CCSDS and ATM protocols. Once the model was verified and the data collected, the results were validated via flight test as part of the USAF Test Pilot School curriculum. Now that the background and methodology have been established, Chapter IV explores and compares the results of the protocol's performance. Flight test results are discussed later, in Chapter VI.

CHAPTER IV - EXPERIMENTAL RESULTS

4.1 Introduction

Chapter III described the methodology used to evaluate the CCSDS protocol. This chapter presents the results of applying that methodology. It begins by describing the initial and secondary sets of transfer frame/source packet/Reed-Solomon configurations executed in the OPNET simulation. Next, it discusses the effects of the various CCSDS parameters on throughput and data quality and uses that knowledge to determine the configurations that will maximize these two measures of performance. The results of this analysis are used to find the configuration of parameters yielding the best compromise between throughput and data quality. Finally, the performance of the CCSDS protocol configured to emulate the data-to-overhead ratio of the basic ATM protocol is compared and analyzed. This chapter presents selected data and hand-drawn curves to illustrate trends in the tested parameters. The raw experimental data in its entirety can be found in Appendix E.

4.2 Initial & Secondary Data Sets

The 73 experimental factor combinations described in Chapter III were executed using the OPNET model designed to replicate the downlink of telemetry data at Edwards AFB. For each configuration the following data was collected: total transmission time, number of source packets transmitted, number of source packets received (intact and within error tolerances), number of idle source packets transmitted, and end-to-end delay for each source packet. From these values the following performance metrics were calculated and/or reported: effective data throughput, data quality, and channel utilization. Although the source packet generation rate was set in each case to achieve near-100% channel utilization, this parameter was measured for the purpose of model verification (and for the sanity of the test conductor).

After completion of the initial data set, additional configurations were run through the simulator to fill in gaps and/or increase the resolution of the initial set of results. This secondary data set is shown in Table 5 below. The results of the secondary data set were used primarily to further illustrate the effects of source packet length on data quality and to more precisely pinpoint peaks in the data quality curves. This is described further in Section 4.4. In all cases, five replications were used, with different random number generator seeds, and the results averaged. Variances were too small to display.

4.3 Analysis of Effective Data Throughput Results

In an attempt to systematically evaluate the effects of the CCSDS parameters on data throughput, the simulation results were first examined with Reed-Solomon encoding turned OFF. As shown in Figure 8, effective throughput was dependent on transfer frame length. In general, throughput increased as transfer frame length increased. In all cases, a transfer frame payload length of 1000 bytes produced the highest throughput. The maximum throughput (with Reed-Solomon encoding OFF) was 108,360 Bps, occurring with a transfer frame length of 1000 bytes and source packet length of 1000 bytes. Beyond a transfer frame payload length of 800 bytes the increase in throughput was small, ranging from only 0.09% boosted performance (with SP = 5 bytes) to 0.48% (with SP = 60,000 bytes). Therefore, if transfer frame length were constrained for other reasons, a payload length of 800 bytes would still provide near-maximum throughput

Table 5. Secondary Data Set to Further Explore Data Quality

Run	TF Len (bytes)	SP Len (bytes)	RS	SP Data Rate (Bps)	Sim Length (sec)	Run	TF Len (bytes)	SP Len (bytes)	RS	SP Data Rate (Bps)	Sim Length (sec)
74	41	50	N	94740	35	122	41	50	Y	24165	35
75	41	100	N	95390	35	123	41	100	Y	24205	35
76	41	150	N	95710	35	124	41	150	Y	24226	35
77	41	300	N	96200	35	125	41	300	Y	24258	35
78	41	700	N	96480	35	126	41	700	Y	24275	35
79	41	1000	N	96540	35	127	41	1000	Y	24280	35
80	41	1400	N	96580	35	128	41	1400	Y	24283	35
81	41	6000	N	96670	35	129	41	6000	Y	24287	35
82	200	50	N	116720	35	130	200	50	Y	67170	35
83	200	100	N	116720	35	131	200	100	Y	67170	35
84	200	150	N	116720	35	132	200	150	Y	67170	35
85	200	300	N	117320	35	133	200	300	Y	67370	35
86	200	700	N	117620	35	134	200	700	Y	67470	35
87	200	1000	N	117720	35	135	200	1000	Y	67500	35
88	200	1400	N	117770	35	136	200	1400	Y	67520	35
89	200	6000	N	117890	35	137	200	6000	Y	67555	35
90	400	50	N	120720	35	138	400	50	Y	87380	35
91	400	100	N	120720	35	139	400	100	Y	87380	35
92	400	150	N	120720	35	140	400	150	Y	87830	35
93	400	300	N	120720	35	141	400	300	Y	87380	35
94	400	700	N	121040	35	142	400	700	Y	87550	35
95	400	1000	N	121140	35	143	400	1000	Y	87610	35
96	400	1400	N	121200	35	144	400	1400	Y	87635	35
97	400	6000	N	121320	35	145	400	6000	Y	87700	35
98	600	50	N	112110	35	146	600	50	Y	97130	35
99	600	100	N	112110	35	147	600	100	Y	97130	35
100	600	150	N	112110	35	148	600	150	Y	97130	35
101	600	300	N	122110	35	149	600	300	Y	97130	35
102	600	700	N	122330	35	150	600	700	Y	97260	35
103	600	1000	N	122330	35	151	600	1000	Y	97260	35
104	600	1400	N	122400	35	152	600	1400	Y	97310	35
105	600	6000	N	122510	35	153	600	6000	Y	97380	35
106	800	50	N	122820	35	154	800	50	Y	102860	35
107	800	100	N	122820	35	155	800	100	Y	102860	35
108	800	150	N	122820	35	156	800	150	Y	102860	35
109	800	300	N	122820	35	157	800	300	Y	102860	35
110	800	700	N	122820	35	158	800	700	Y	102860	35
111	800	1000	N	122990	35	159	800	1000	Y	102980	35
112	800	1400	N	122990	35	160	800	1400	Y	102980	35
113	800	6000	N	123110	35	161	800	6000	Y	103060	35
114	1000	50	N	123250	35	162	1000	50	Y	106640	35
115	1000	100	N	123250	35	163	1000	100	Y	106640	35
116	1000	150	N	123250	35	164	1000	150	Y	106640	35
117	1000	300	N	123250	35	165	1000	300	Y	106640	35
118	1000	700	N	123250	35	166	1000	700	Y	106640	35
119	1000	1000	N	123390	35	167	1000	1000	Y	106740	35
120	1000	1400	N	123390	35	168	1000	1400	Y	106740	35
121	1000	6000	N	123480	35	169	1000	6000	Y	106810	35

TF Len = transfer frame payload length in bytes; SP Len = source packet payload length in bytes; RS = Reed-Solomon (N = off, Y = on); SP Data Rate = source packet generation rate in bytes per second (based on 100% channel utilization)

performance. Going one step further, a transfer frame payload length of 600 bytes degraded throughput performance by less than 0.75% for all source packet payload lengths. Stated simply, these results suggest that while a transfer frame payload length of 1000 bytes should produce the highest throughput performance, if other constraints limit transfer frame payload length, the user should still get within 0.75% of maximum throughput performance with transfer frame payload lengths as low as 600 bytes. (Note: For a transfer frame payload length of 400 bytes, throughput was degraded up to 2.01%, and up to 4.7% for a payload length of 200 bytes.)

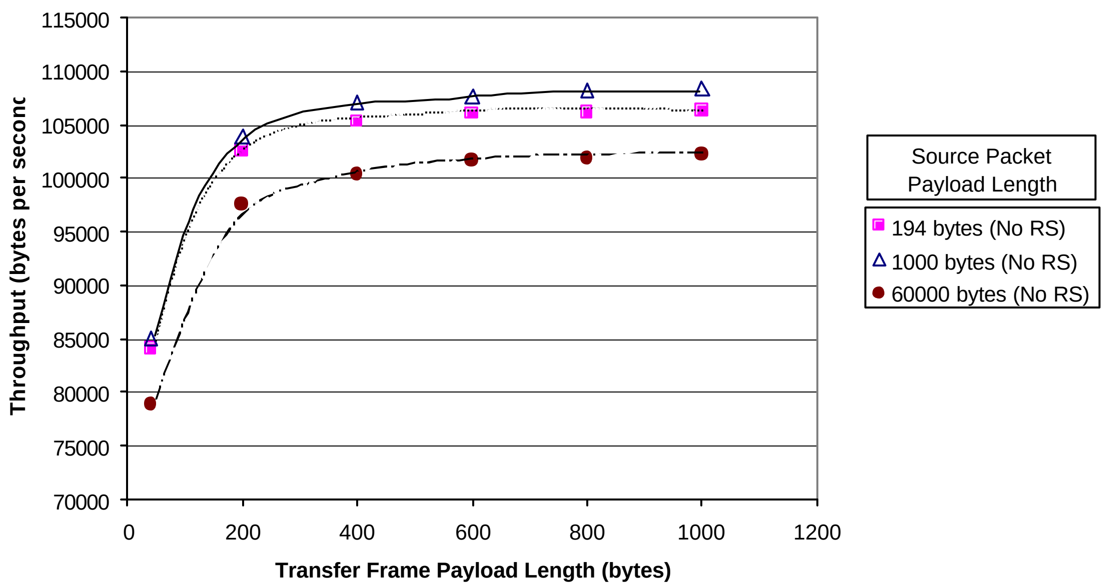


Figure 8. Throughput Performance Variation with Transfer Frame Payload Length

(Trendlines shown are hand-drawn)

Figure 9 shows that effective data throughput also varied with source packet length. For the most part, throughput performance was the highest for source packet payload lengths between 500 and 2000 bytes, and fell off for payload lengths below 500 bytes and above 2000 bytes. A source packet length of 1000 bytes consistently yielded the highest throughput. The percentage difference in throughput for source packet payload lengths between 500 and 2000 bytes, however, was very small. The difference in throughput was at worst 0.38%, and on average the difference was only 0.12%. With a variation this small, the benefit gained in finding a precise peak is most likely not worth the time and resources to find it. These results suggest that to maximize throughput performance source packet payload length should be set to 1000 bytes; however given other constraints, a source packet payload length between 500 and 2000 bytes will also yield top throughput performance.

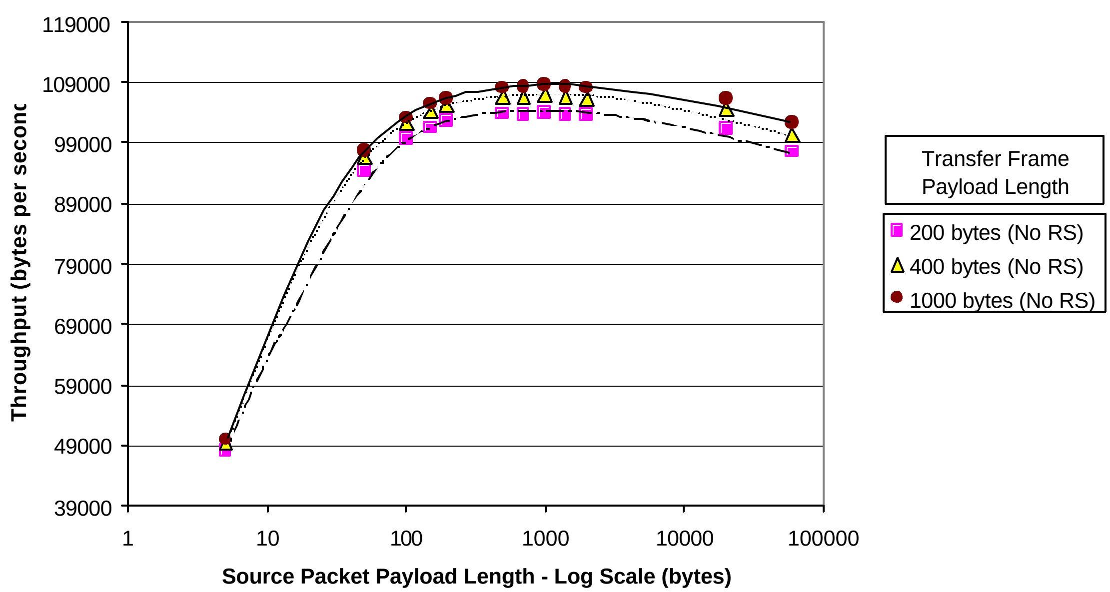


Figure 9. Throughput Performance Variation with Source Packet Payload Length

(Trendlines shown are hand-drawn)

The effects of adding Reed-Solomon encoding are shown in Figure 10 through Figure 13. In general, when Reed-Solomon encoding was turned ON, the overall trends were similar to the Reed-Solomon OFF cases, however, throughput performance was lower. The best throughput attained with Reed-Solomon ON was 95,542 Bps, occurring at a transfer frame payload length of 1000 bytes and source packet payload length of 2000 bytes.

With regards to transfer frame length (Figure 10), throughput with Reed-Solomon ON increased as transfer frame length increased, with a payload length of 1000 bytes still producing the highest throughput. In all but one case (TF = 41 bytes), better throughput performance was attained with Reed-Solomon encoding turned OFF. As shown in Figure 11, the best throughput achieved with Reed-Solomon encoding OFF was 12% higher than the best case with Reed-Solomon encoding ON.

Similar results occurred with regards to source packet length. As shown in Figure 12, the throughput versus source packet length curve had the same basic shape as the Reed-Solomon OFF case, with the highest throughput occurring for the range of source packet payload lengths of 500 - 2000 bytes. One difference between this and the Reed-Solomon OFF case was that a source packet payload length of 1400 bytes generally produced the highest throughput, versus 1000 bytes in the Reed-Solomon OFF case. In all but one case (TF = 41 bytes) better throughput performance was attained with Reed-Solomon encoding turned OFF. And again, as shown in Figure 13, the best throughput achieved with Reed-Solomon encoding OFF was 12% higher than the best case with Reed-Solomon encoding ON.

Although throughput performance with Reed-Solomon encoding turned ON was higher for the single case of TF = 41, this transfer frame length in general produced the lowest throughput of all possible transfer frame lengths with both Reed-Solomon ON and OFF, and would therefore not be chosen as a possible solution. These results therefore suggest that given similar channel error characteristics, to achieve maximum throughput performance, Reed-Solomon encoding should be OFF.

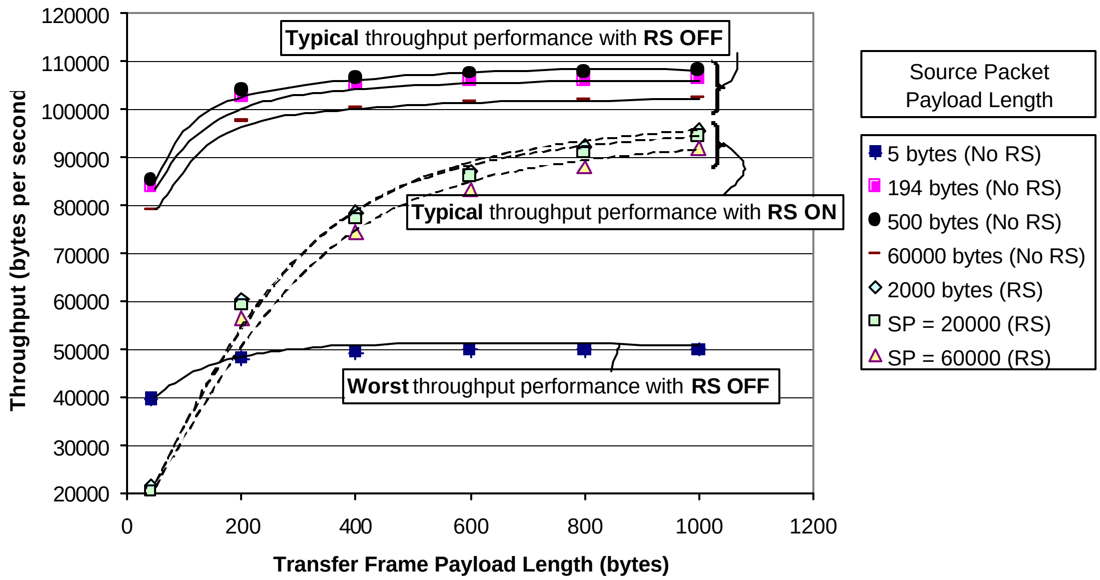


Figure 10. Effect of Reed-Solomon Encoding on Throughput (via Transfer Frame Length)

(Trendlines shown are hand-drawn)

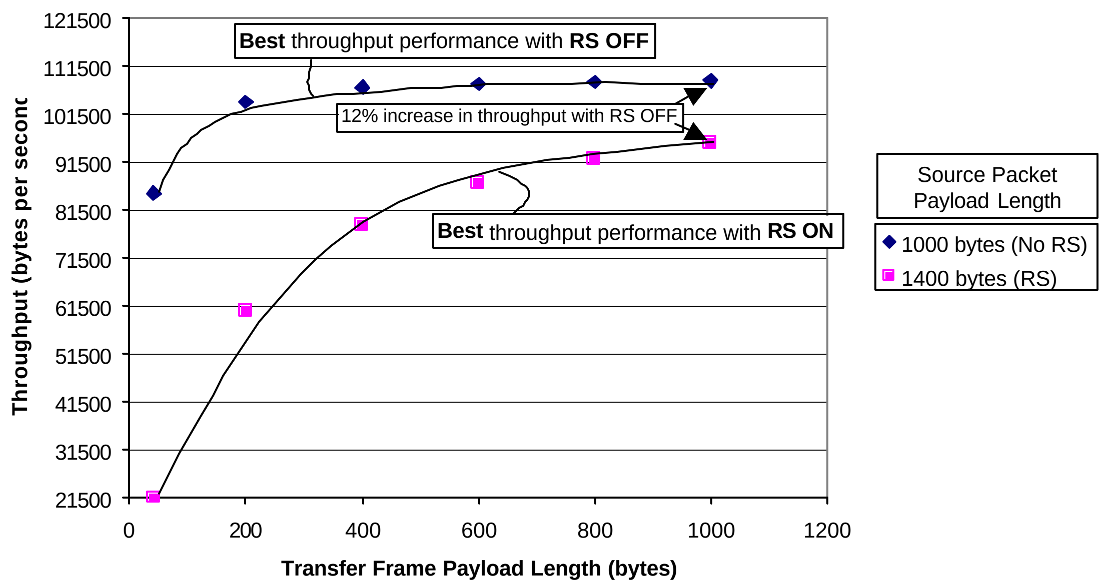


Figure 11. Comparison of Throughput With/Without Reed-Solomon Encoding - 1

(Trendlines shown are hand-drawn)

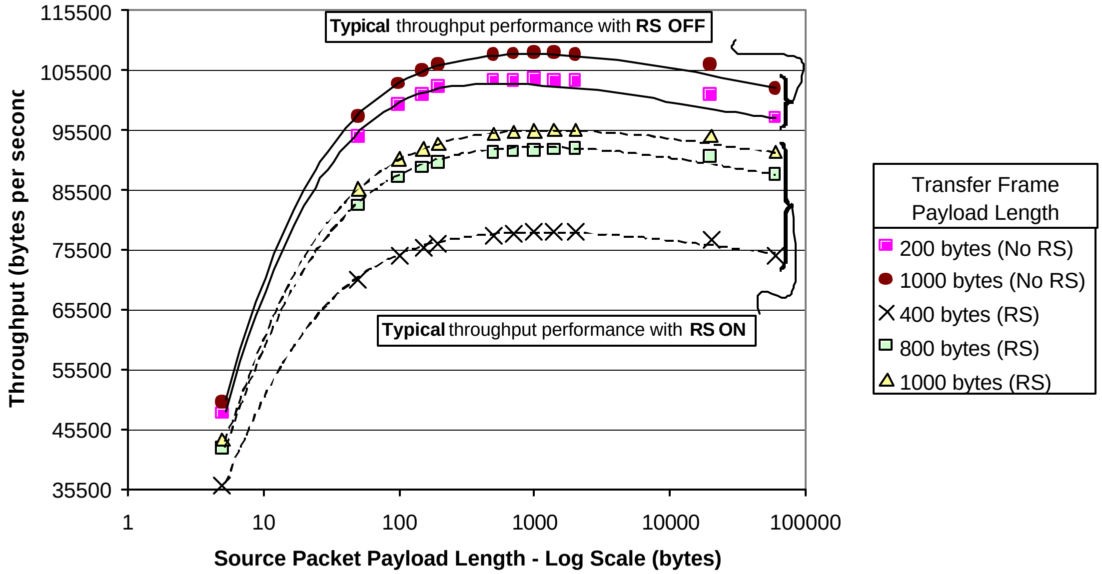


Figure 12. Effect of Reed-Solomon Encoding on Throughput (via Source Packet Length)

(Trendlines shown are hand-drawn)

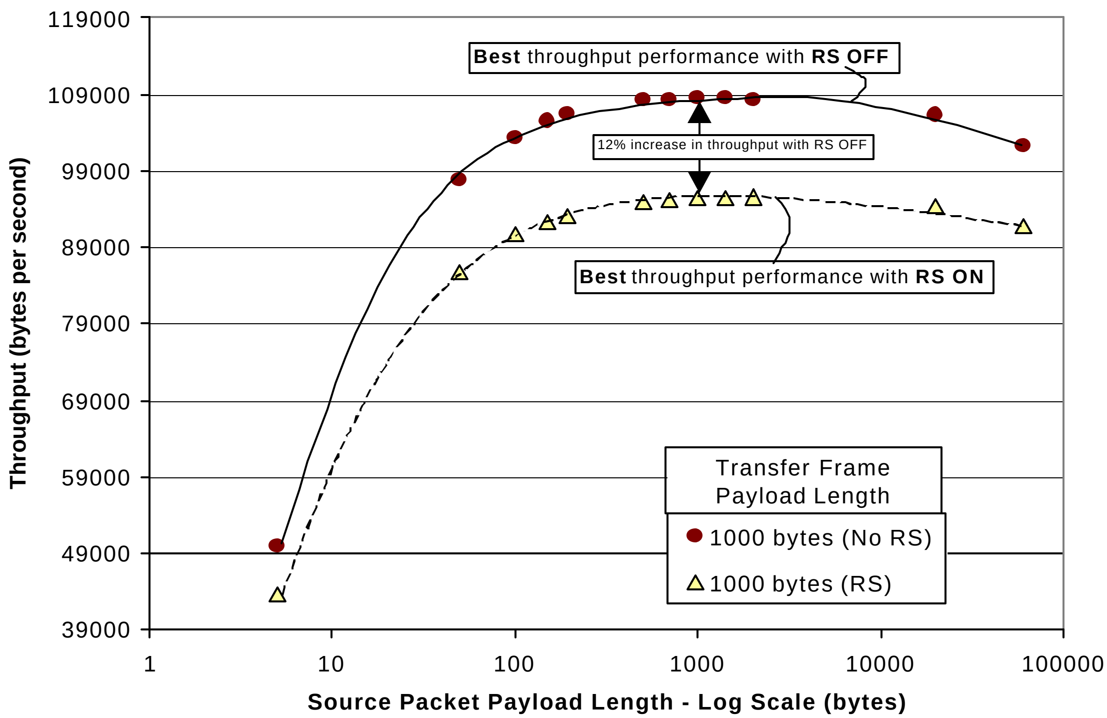


Figure 13. Comparison of Throughput With/Without Reed-Solomon Encoding - 2

(Trendlines shown are hand-drawn)

Figure 14 is a contour plot of the simulation data. Only the Reed-Solomon OFF results are plotted. The plot supports the previous conclusions. In the plot, the region of highest throughput occurs for transfer frame payload lengths from approximately 600 to 1000 bytes, with throughput increasing as transfer frame payload lengths approach 1000 bytes. Source packet payload lengths for best throughput ranged from about 500 to 2000 bytes (27 to 33 on the log scale). This plot will be used again later to find the CCSDS configuration that yields the best compromise between throughput and data quality.

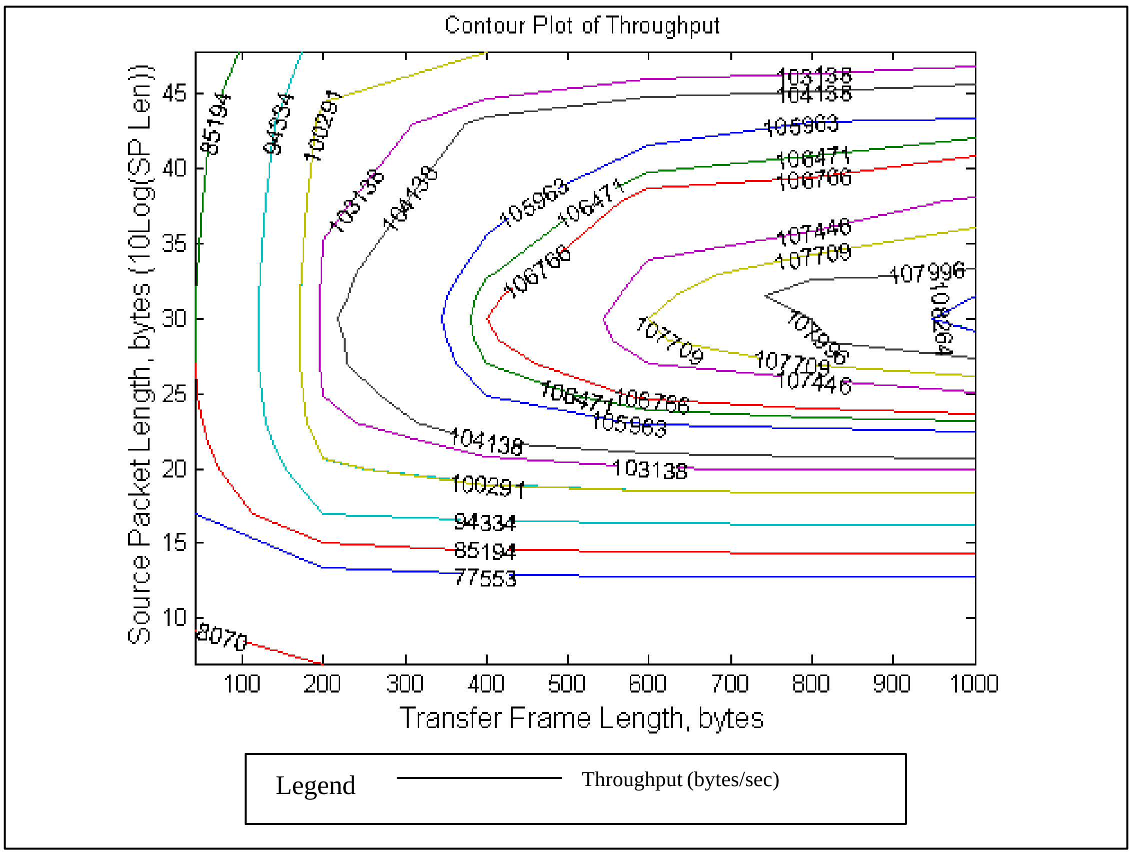


Figure 14. Contour Plot - Throughput Variation With CCSDS Parameters

ANOVA analysis on the collected data showed that transfer frame length contributed 36.4% to the resulting throughput, source packet length 20.8%, and Reed-

Solomon encoding 31.0%. The remaining 12% was due primarily to the interaction between transfer frame length and Reed-Solomon encoding. The complete ANOVA table is provided in Appendix F.

The results of the modeling and simulation suggest the following conclusions with regards to maximizing effective data throughput:

1. Reed-Solomon encoding should be OFF for maximum throughput performance.
2. A transfer frame payload length between 600 and 1000 bytes should be used to obtain top throughput performance.
3. A source packet payload length between 500 and 2000 bytes should be used to obtain top throughput performance.
4. Ultimate solution: Barring other constraints, a transfer frame payload length of 1000 bytes, source packet payload length of 1000 bytes, and Reed-Solomon encoding OFF should be used to obtain the highest effective data throughput.

4.4 Analysis of Data Quality Results

To systematically evaluate the effects of the CCSDS parameters on data quality, the simulation results were first examined with Reed-Solomon encoding turned OFF. Figure 15 shows the effect of transfer frame payload length on data quality. Overall, there was no substantial correlation between transfer frame length and the resulting data quality. Variation in data quality over each data set ranged only from 0.004 to 0.51 and ANOVA analysis of the collected data indicated that transfer frame payload length contributed only 0.015% to the resulting data quality. These statistics corroborate the straight-line nature of the data plotted in Figure 15.

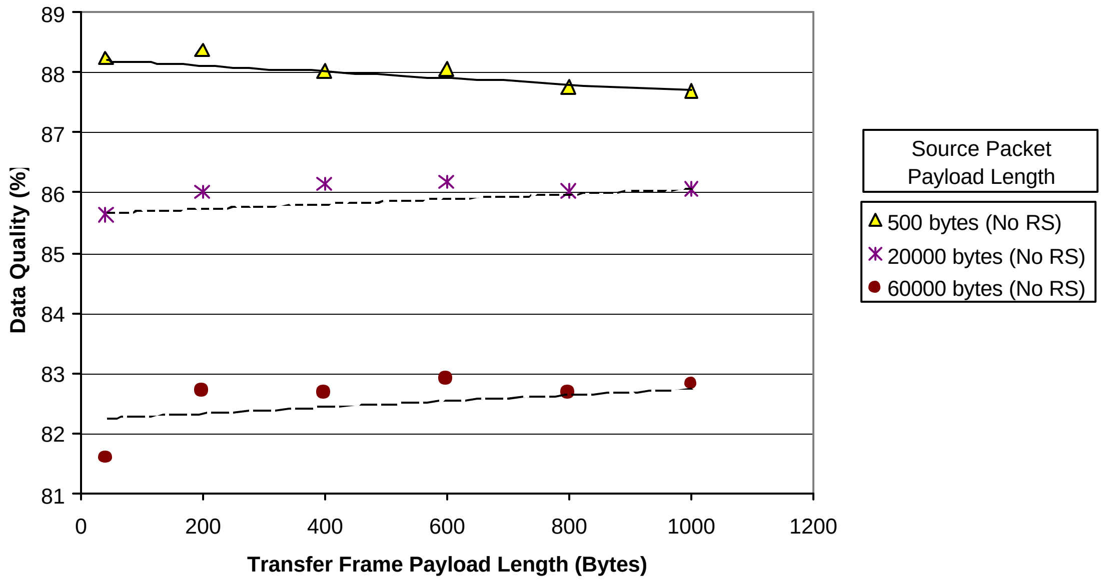


Figure 15. Data Quality Variation with Transfer Frame Payload Length

(Trendlines shown are hand-drawn)

Figure 16 shows the effect of source packet length on data quality. To get a better view of what was going on, the TF = 41 point was eliminated and the plot rescaled. Figure 17 shows the result. Data quality was the highest for source packet lengths between 500 and 2000 bytes, and fell off for source packet lengths below 500 bytes and above 2000 bytes. The highest data quality was consistently achieved with a source packet length of 1000 bytes. The maximum data quality (with Reed-Solomon encoding OFF) was 88.25%, occurring with a source packet length of 1000 bytes and transfer frame length of 200 bytes. The variance in data quality over the range of 500 to 2000 bytes was very small, ranging from 0.0046 to 0.033. Therefore, for top data quality performance these results suggest a source packet payload length between 500 and 2000 bytes should be chosen, with 1000 bytes being optimum.

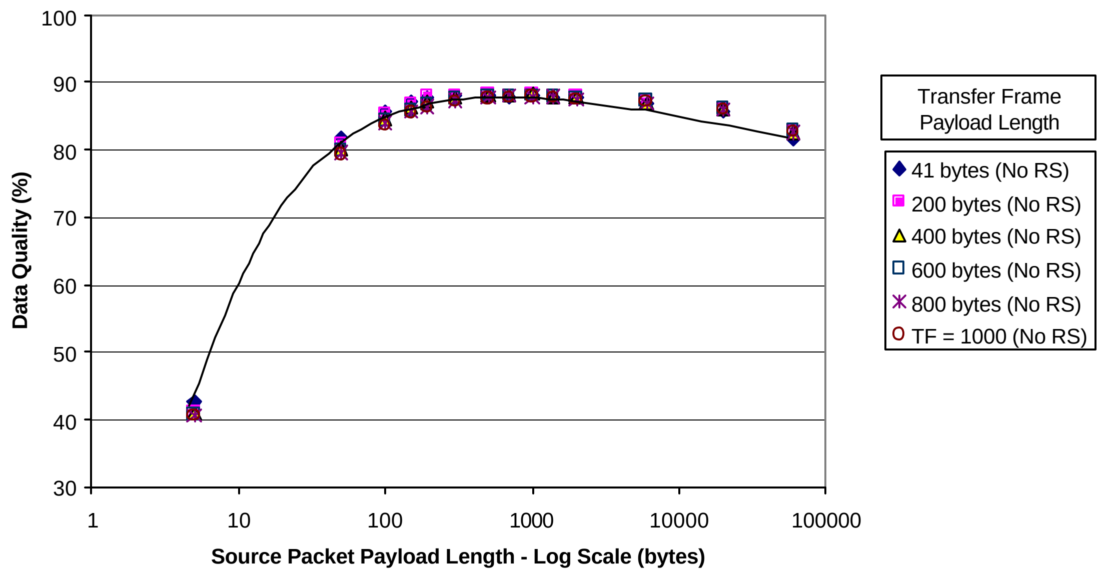


Figure 16. Data Quality Variation with Source Packet Payload Length - 1

(Trendlines shown are hand-drawn)

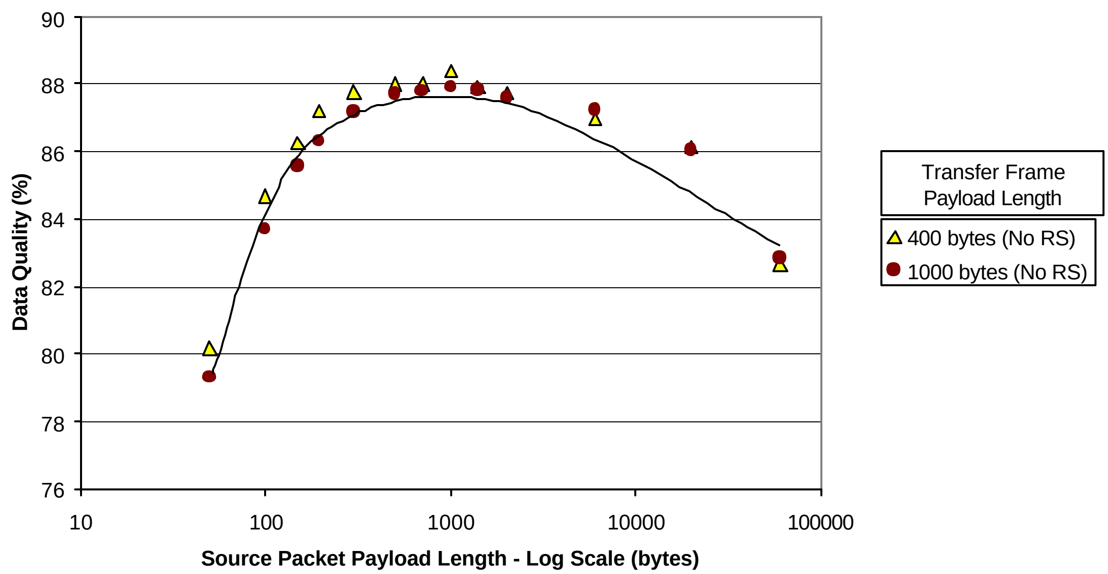


Figure 17. Data Quality Variation with Source Packet Payload Length - 2

(Trendlines shown are hand-drawn)

The effects of adding Reed-Solomon encoding are shown in Figure 18 - Figure 20. In general, data quality was higher with Reed-Solomon ON, but the average amount of improvement was less than 2%. The best data quality achieved with Reed-Solomon ON was 89.59%. This occurred with a source packet payload length of 1400 bytes and transfer frame payload length of 400 bytes.

With regards to transfer frame length, there was again very little correlation between transfer frame length and data quality. Data quality was consistently higher with Reed-Solomon encoding ON, as shown in Figure 18. Although higher, the improvement gained using Reed-Solomon was relatively small. As shown in Figure 19, the best data quality achieved with Reed-Solomon encoding ON was only 1.52% higher than the best case with Reed-Solomon encoding OFF.

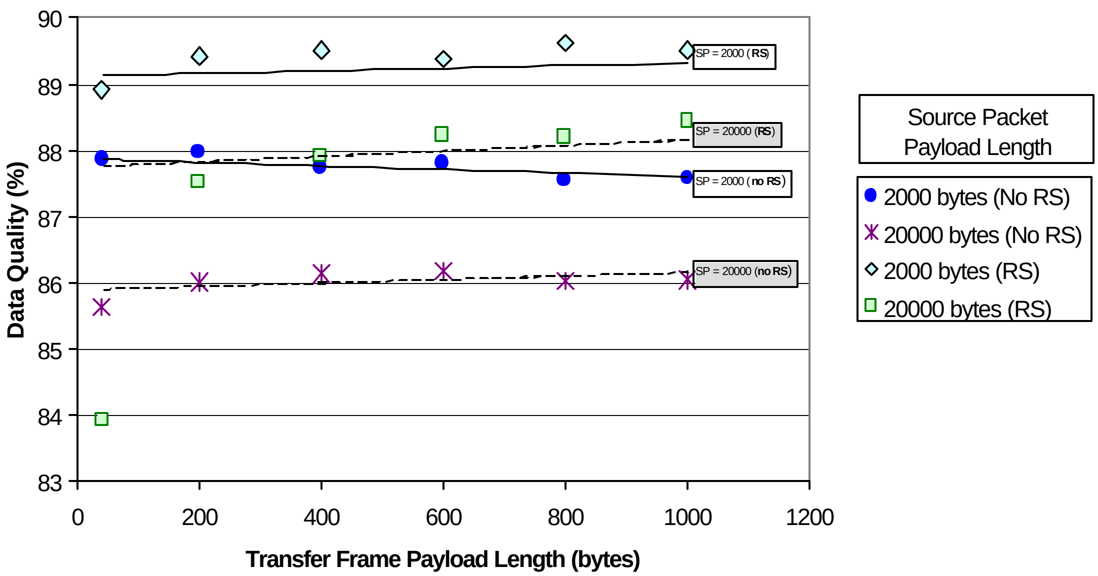


Figure 18. Effects of Reed-Solomon Encoding on Data Quality (via Transfer Frame Length)

(Trendlines shown are hand-drawn)

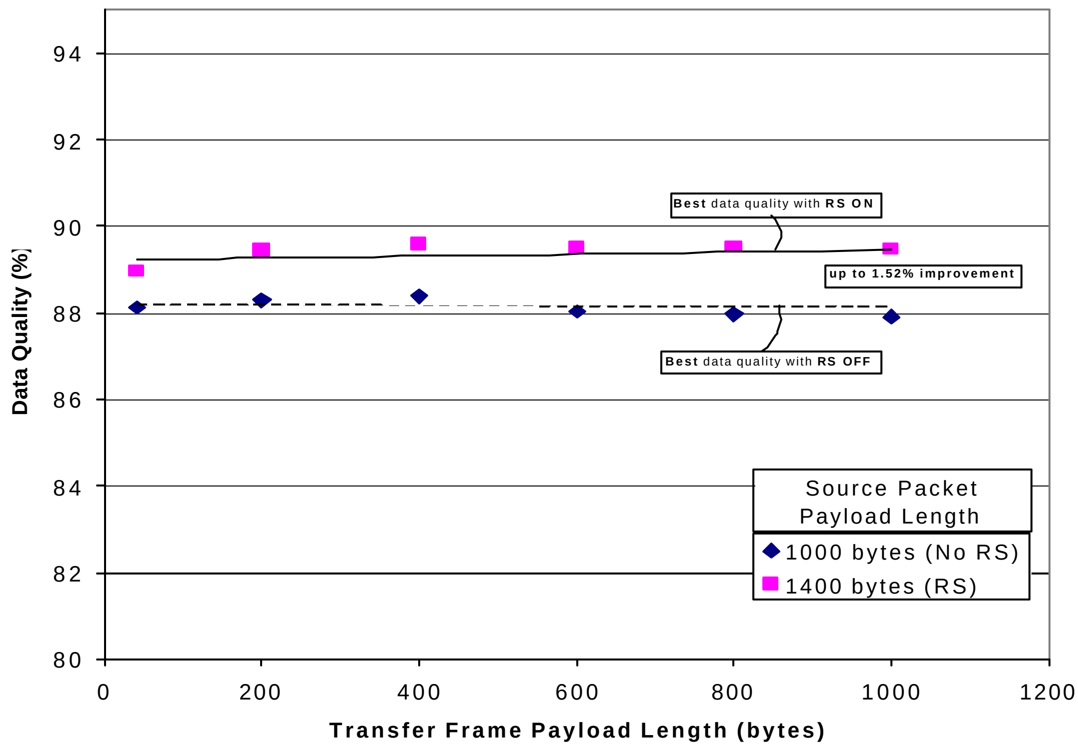


Figure 19. Comparison of Best Data Quality With/Without Reed-Solomon Encoding

(Trendlines shown are hand-drawn)

As shown in Figure 20, the data quality versus source packet length curve had the same basic shape as the Reed-Solomon OFF case, with the highest data quality occurring in the range of source packet payload lengths of 500 - 2000 bytes. One difference between this and the Reed-Solomon OFF case was that a source packet payload length between 1400 - 2000 bytes generally produced the highest throughput, versus 1000 bytes in the Reed-Solomon OFF case. This plot again shows that although data quality was higher with Reed-Solomon ON, the improvement was less than 2%.

These results suggest two things. First, in order to maximize data quality, Reed-Solomon encoding should be ON. Second, given that the improvement in data quality was relatively small, and that data quality will inevitably be driven by the channel BER as witnessed here where the error-free percentage was generally 88% and the top data quality achieved also fell in the vicinity of 88%, in the presence of other constraints, near-top data quality performance is achievable with Reed-Solomon OFF.

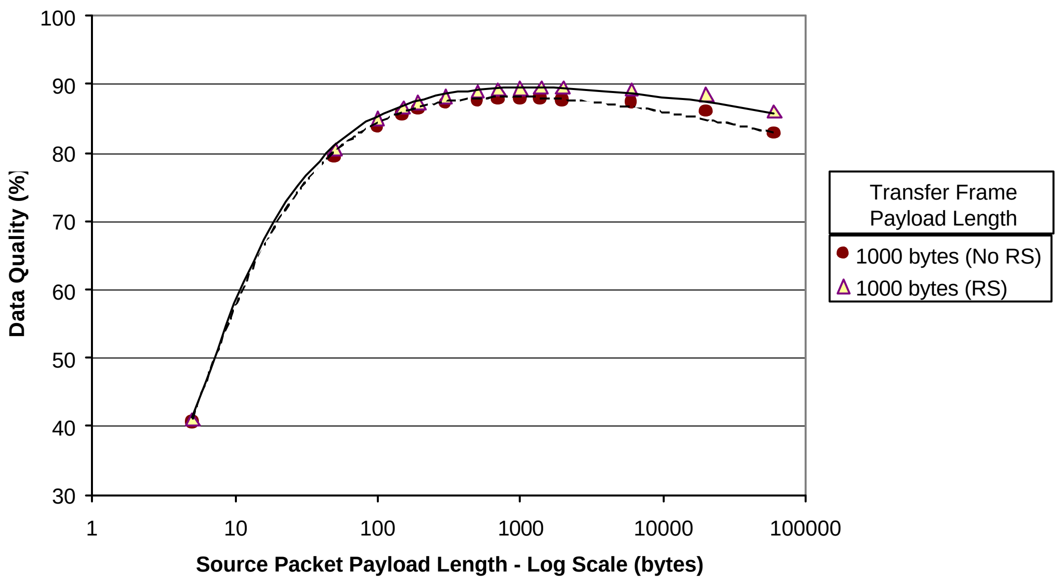


Figure 20. Effects of Reed-Solomon Encoding on Data Quality (via Source Packet Length)

(Trendlines shown are hand-drawn)

Figure 21 and Figure 22 are contour plots of the simulation data with and without Reed-Solomon encoding, respectively. The plot supports the previous conclusions. The slopes of the results are extremely shallow indicating that changing transfer frame and source packet length has little effect on data quality. In the plot, the region of highest data quality occurs for source packet payload lengths from approximately 500 to 2000 bytes (27 to 33 on the log scale), with data quality fairly even throughout the range. This plot will be used again later to find the CCSDS configuration that yields the best compromise between throughput and data quality.

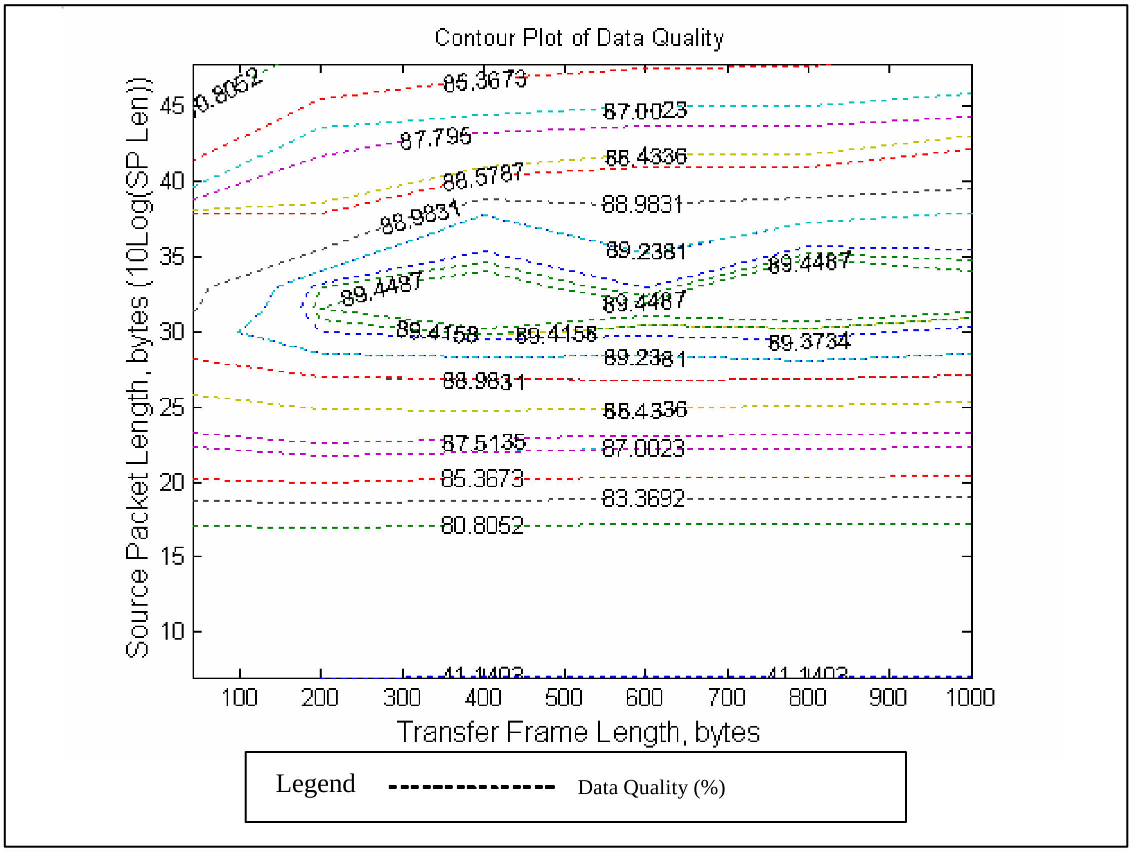


Figure 21. Contour Plot of Data Quality Variation With Reed-Solomon ON

ANOVA analysis on the collected data showed that source packet length contributed 99.3% to the resulting data quality, transfer frame length 0.015%, and Reed-Solomon encoding 0.15%. The remaining 0.5% was due primarily to the interactions between transfer frame and source packet length. These statistics support the results discussed in this section. The complete ANOVA table is provided in Appendix F.

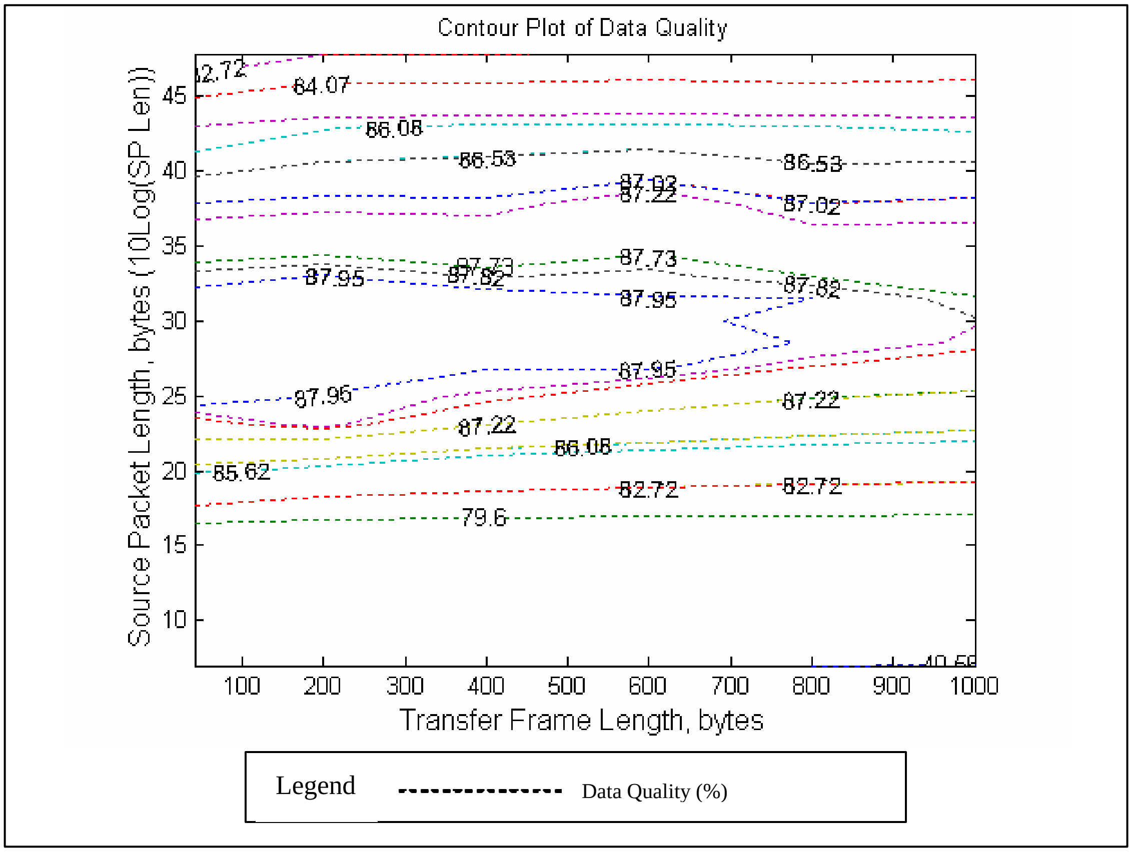


Figure 22. Contour Plot of Data Quality Variation with Reed-Solomon OFF

The results of the modeling and simulation suggest the following conclusions with regards to maximizing data quality:

1. Transfer frame length has a negligible affect on the resulting data quality.
2. Reed-Solomon encoding should be ON for maximum data quality.
3. Near-maximum data quality (within 2% of maximum) is achievable with Reed-Solomon encoding OFF.
4. A source packet payload length between 500 and 2000 bytes should be used to obtain top data quality performance.

5. Ultimate Solution: A source packet payload length of 1400 bytes with Reed-Solomon encoding ON should be used to obtain the highest data quality.
6. Runner-Up Solution: A source packet payload length of 1000 bytes with Reed-Solomon encoding OFF can be used to obtain top data quality results.

4.5 Best Tradeoff Between Throughput & Data Quality

To determine the CCSDS configuration that would offer the user the best compromise between throughput and data quality performance, the primary assumption was that the two performance requirements were equally weighted in priority. In reality, this may not always be the case; determining the best configuration for varying cases of priority is left to future study.

To aid in the determination of a "best compromise" CCSDS configuration, two methods were used. The first method was to take the two contour plots used to individually evaluate throughput and data quality and overlay them to qualitatively find the area(s) where both performance metrics faired particularly well. The second method used the statistical software Design Expert [8]. This software, which was also used to execute the ANOVA analysis on the data in previous sections, contained a function for listing the data points (i.e., combination of CCSDS parameters) according to a pre-defined sorting requirement, for example "maximize throughput", "maximize data quality", or "maximize throughput and data quality". Using this last option, the Design Expert software provided its solution to the problem. One limitation to this method was that the software would only choose its solution from among the data points in the original matrix structure of possible parameter values (i.e., source packet length equals 5, 50, 100, 150, 194, 300, 500, 700, 1000, 1400, 2000, 6000, 20000, or 60000 only). In other words, it was not able to interpolate over the entire range of possible values (i.e., source packet length can be anywhere between 5 and 60000) and choose a solution that was not within its matrix of possible parameter configurations. Nonetheless, the software was used to provide a rough verification of the results of the first method. Both methods yielded similar results.

4.5.1 First Method - Overlay of Contour Plots

Figure 23 and Figure 24 show an overlay of the contour plots used to analyze throughput (Figure 14) and data quality (Figure 21 and Figure 22). Figure 23 is with Reed-Solomon ON, Figure 24 with it OFF. Examination of the two figures shows that the greater region of overlap between best throughput and data quality occurs when Reed-Solomon is OFF. This makes sense from the previous analysis of throughput and data quality. Although Reed-Solomon offered a slight improvement in data quality, it severely degraded throughput performance. Therefore, the search for a best combined performance solution will be made with Reed-Solomon encoding OFF.

Since previous analysis indicated that data quality did not vary significantly with transfer frame length, it is not surprising that the best combined performance occurred at the same transfer frame lengths for optimum throughput performance, namely 600 to 1000 bytes. This was true regardless of whether Reed-Solomon was used.

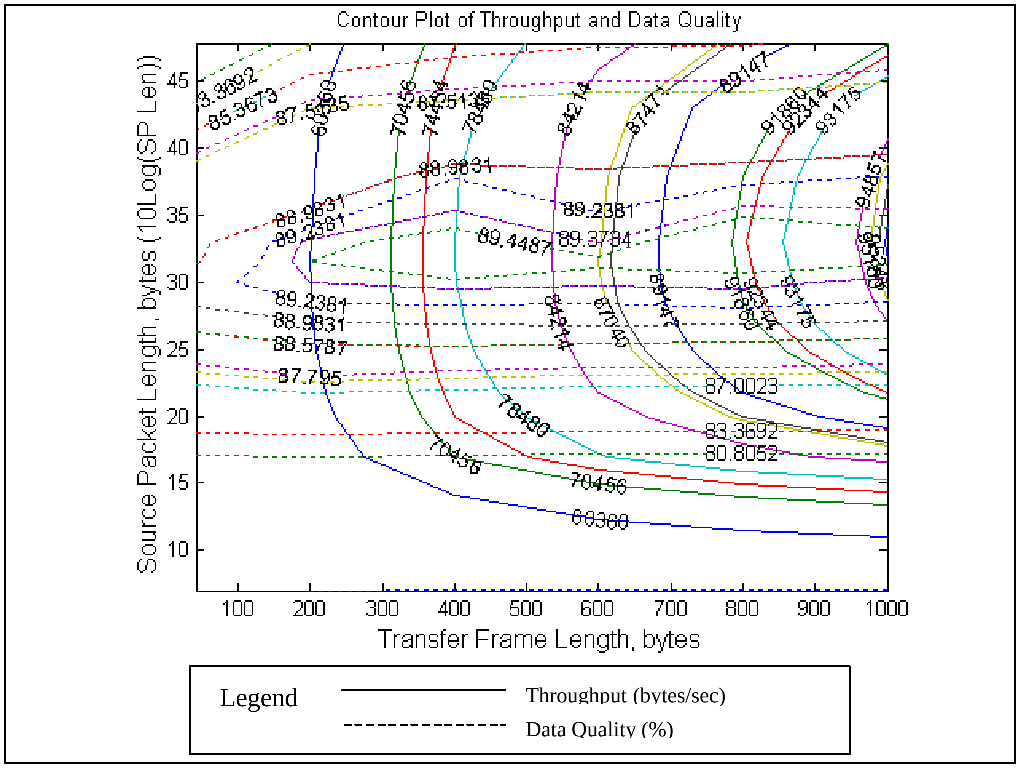


Figure 23. Contour Plot of Combined Performance With Reed-Solomon ON

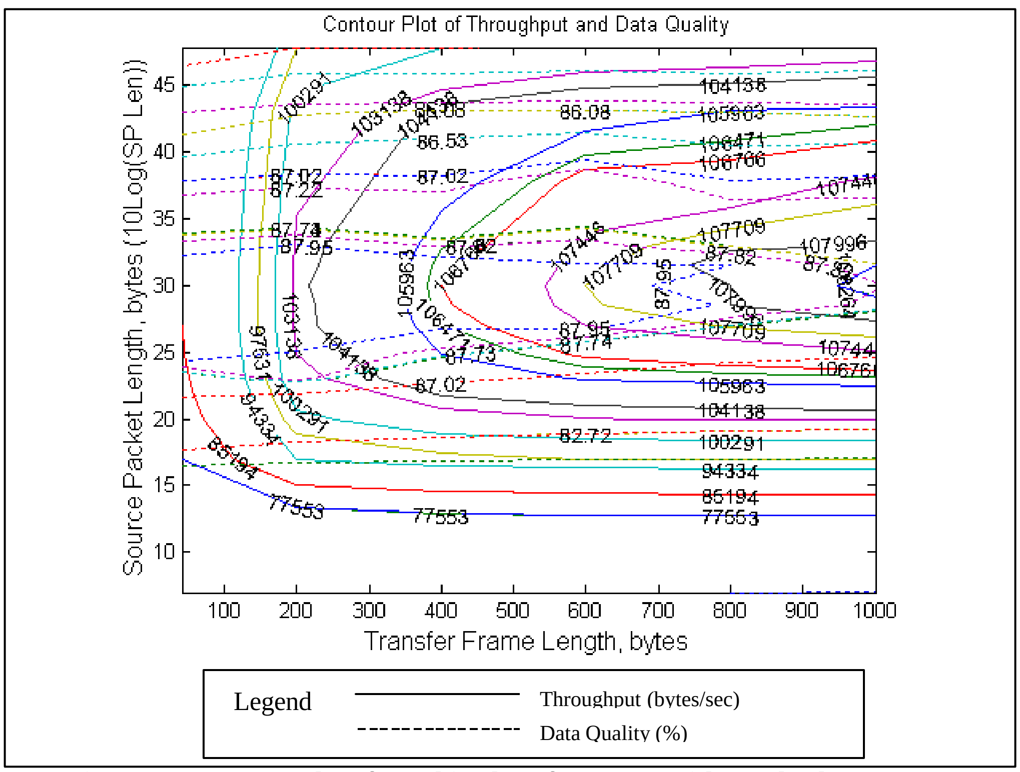


Figure 24. Contour Plot of Combined Performance With Reed-Solomon OFF

With Reed-Solomon OFF, the source packet payload lengths yielding the best combined performance were approximately 500 to 2000 bytes. The reason that the source packet length for optimum throughput performance matched that for the best combined performance is less obvious, until observing the contour plot. In the area corresponding to a transfer frame payload length of 600-1000 bytes and source packet payload lengths between 500-2000 bytes, the slope of data quality results are extremely shallow when compared to those of throughput results. This indicates that changing source packet payload length from 500 bytes to 2000 bytes would have very little effect on data quality but could noticeably improve throughput.

In summary, these results suggest that to achieve the best combined throughput and data quality, transfer frame payload length should be between 600-1000 bytes, source packet payload length should be from 500-2000 bytes, and Reed-Solomon encoding OFF.

4.5.2 Second Method - Statistical Software Solution

The second method to find a "best compromise" solution used the statistical software Design Expert [8]. When attempting to maximize both throughput and data quality, Design Expert offered the following guidance: transfer frame payload length between 400 and 1000 bytes; source packet payload length between 500 and 1400 bytes, and Reed-Solomon encoding OFF. In general, these results agreed with the analysis of the contour plots.

Taking the most conservative of the solutions, to maximize both throughput and data quality, the results of both the contour plot analysis and Design Expert guidance suggest that transfer frame payload length should be between 500 to 1000 bytes, with

1000 bytes being the best. Source packet payload length should be between 500 and 1400 bytes, with 1000 bytes yielding the best performance in the Design Expert analysis, and Reed-Solomon encoding should be OFF.

4.6 ATM vs CCSDS - A Performance Comparison

Table 6 shows how the "ATM-version" of CCSDS faired in comparison to the best performance of the unadulterated CCSDS protocol. As discussed in Chapter III, the CCSDS configuration used in the "ATM-version" was a transfer frame payload length of 179 bytes, a source packet payload length of 173 bytes, and Reed-Solomon encoding OFF. Derivation of these values can be found in Appendix D. The CCSDS configuration used for the comparison was a transfer frame payload length of 1000 bytes, a source packet payload length of 1000 bytes, and Reed-Solomon encoding OFF. This configuration was chosen because it produced the best compromise between throughput and data quality (see Section 4.5). It should be noted that the best throughput achieved overall was 108,360 Bps (see Section 4.3), and best data quality achieved (in other than the ATM configuration) was 89.59% (see Section 4.4). Since no configuration of CCSDS parameters achieved both of these levels of performance simultaneously, the "ATM-version" was compared to the "best of both worlds" configuration. For completeness, however, the "ATM-version" of CCSDS generated 7.35% lower throughput than the maximum achievable, and 0.11% higher data quality.

The results of the performance comparison suggest that further exploration of using ATM, or an ATM-CCSDS hybrid, in the DoD test range community is warranted. Data quality in the ATM configuration was essentially the same. While the throughput performance of the ATM protocol was lower than that of CCSDS in this study, the results were "close enough" that with further "tuning" the ATM protocol may be able to offer comparable throughput performance. It is also worth noting that the performance differences here may be caused by differences between the OPNET model and real-world test range conditions and channel BER. Chapter VI presents the flight test results in the area of ATM/CCSDS comparison.

Table 6. ATM vs CCSDS - A Performance Comparison

Protocol	Transfer Frame Payload Length (Bytes)	Source Packet Payload Length (Bytes)	Data Quality (%)	Throughput (Bps)
CCSDS	1000	1000	87.83	108,360.00
ATM	179	173	87.70	101,572.76
		Percent Difference =	-0.15%	-6.26%

4.7 Summary

This chapter has established the performance of the CCSDS protocol in the DoD test range environment. It has also attempted to give the user guidance and a starting point for configuring the protocol's parameters to best satisfy mission needs. The results of this analysis are summarized in Table 7 below. Finally, this chapter established a baseline for the performance of the ATM protocol in the DoD test range environment. With further research, it is possible the ATM protocol, alone or in combination with the CCSDS protocol, could expand telemetry downlink performance for the military test community.

Table 7. Summary of Modeling and simulation Results

Priority Level of Mission Rqmts		Reed-Solomon (on/off)	TF Payload Length (Bytes)	SP Payload Length (Bytes)	Best Performing Configuration	Other Top Performing Configurations
Throughput	Data Quality					
100%	0%	ON	Not Recommended		RS: OFF TF: 1000 SP: 1000	
		OFF	600 - 1000	500 - 2000		
50%	50%	ON	Not Recommended		RS: OFF TF: 1000 SP: 1000	
		OFF	600 - 1000	500 - 1400		
0%	100%	ON	Any	500 - 2000	RS: ON TF: 1000 SP: 1400	RS: OFF TF: 1000 SP: 1000
		OFF	Any	500 - 2000		

CHAPTER V - CONCLUSIONS & RECOMMENDATIONS PRIOR TO FLIGHT TEST

5.1 Introduction

The goal of this research was to evaluate the CCSDS protocol for use in the DoD test community and attempt to optimize it for specific mission objectives. Three CCSDS parameters were identified as having a potentially significant effect on the performance of the protocol. These parameters were: transfer frame length, source packet length, and Reed-Solomon encoding. Each parameter was evaluated to determine what role it played in the overall performance of the protocol, which was measured in terms of throughput and data quality. A summary of the findings can be found below. A detailed explanation of the three parameters, as well as the two measures of protocol performance, can be found in Chapters II and III. Specific details leading to the conclusions listed below can be found in Chapter IV.

5.2 Summary of Key Results

This research effort was broken into four main areas. The first area of study focused on how the three CCSDS parameters (transfer frame length, source packet length, and Reed-Solomon encoding) affect data throughput and how each parameter should be set in order to maximize throughput. This knowledge is of particular use to a mission where maximizing the throughput of mission data is of particular priority for meeting mission objectives (e.g., "video" data). With regards to throughput, the following conclusions were made based on the modeling and simulation results:

1. Reed-Solomon encoding should be OFF for maximum throughput performance.
2. A transfer frame payload length between 600 and 1000 bytes should be used to obtain top throughput performance.
3. A source packet payload length between 500 and 2000 bytes should be used to obtain top throughput performance.
4. Ultimate solution: Barring other constraints, a transfer frame payload length of 1000 bytes, source packet payload length of 1000 bytes, and Reed-Solomon encoding OFF should be used to obtain the highest effective data throughput.

The second area of study focused on how the three CCSDS parameters affected data quality and how each should be set in order to maximize data quality. This knowledge is of particular use to a mission where maximizing the amount of mission data transmitted without error is of particular priority for meeting mission objectives (e.g., "memory" data). With regards to data quality, the following conclusions were made based on the modeling and simulation results:

1. Transfer frame length has a negligible effect on the resulting data quality.
2. Reed-Solomon encoding should be ON for maximum data quality.
3. Near-maximum data quality (within 2% of maximum) is achievable with Reed-Solomon encoding OFF.
4. A source packet payload length between 500 and 2000 bytes should be used to obtain top data quality performance.

5. Ultimate Solution: A source packet payload length of 1400 bytes with Reed-Solomon encoding ON should be used to obtain the highest data quality.
6. Runner-Up Solution: A source packet payload length of 1000 bytes with Reed-Solomon encoding OFF can be used to obtain top data quality results.

The third area of study focused on how the three CCSDS parameters affect both data throughput and data quality simultaneously and how each should be set in order to obtain the best simultaneous throughput and data quality. For this evaluation, throughput and data quality were given equal weighting. This knowledge is of particular use to a mission where both throughput and data quality are important to meeting mission objectives. With regards to finding a “best of both worlds” solution, the following conclusions were made based on the modeling and simulation results:

1. To achieve the best compromise between throughput and data quality, transfer frame payload length should be between 600 and 1000 bytes.
2. To achieve the best compromise between throughput and data quality, source packet payload length should be between 500 and 1400 bytes.
3. To achieve the best compromise between throughput and data quality, Reed-Solomon encoding should be OFF.
4. A transfer frame length of 1000 bytes, source packet length of 1000 bytes, and Reed-Solomon encoding OFF should be used to obtain an optimum combination of throughput and data quality.

The final area of study focused on comparing the CCSDS and ATM packet protocols. This was done to determine whether future work towards using the ATM protocol in the test range community in conjunction with, or instead of, the CCSDS protocol is justified. The two protocols were compared in terms of throughput and data quality. Overall, performance of the ATM protocol was sufficiently close to that of CCSDS to warrant further investigation. In this study, throughput attained using the ATM-version was 6.26% lower than that with CCSDS and data quality was -0.15% lower.

5.3 Recommendations for Further Research

Results show the CCSDS packet telemetry protocol to be effective for the transmission of telemetry data in the DoD test range community. The relationships between the primary CCSDS parameters (transfer frame length, source packet length, and Reed-Solomon encoding) and the resulting protocol performance (measured in terms of throughput and data quality) were mapped and general conclusions made with regards to optimizing the protocol to meet mission needs. This research meets the need of the test community for configuring equipment for sorties involving telemetry data transmission. Suggestions for future areas of work are provided below for continued study and to optimize the CCSDS protocol.

In the conduct of this research, the Edwards AFB test range was modeled using the OPNET modeling tool. Due to the constraints of the software and scope of the research, certain simplifying assumptions were made and the influence of certain environmental parameters eliminated or grouped under the umbrella of “channel BER”.

These parameters included aircraft altitude and range from the receiver, the antenna pattern on the aircraft, weather, and test range location. All of these parameters serve to effectively improve or worsen channel BER, however the specific effects each one has on overall performance was not explicitly evaluated. They did, however, come into play during the flight test portion. For this reason there is value to be gained from evaluating the effects of these factors further.

A model of the channel BER at Edwards AFB was an integral part of the OPNET model used to evaluate the CCSDS protocol. The 88-10-2 breakdown of channel errors used in the model was based as closely as possible on previous work by the ARTM JPO to characterize the channel. Characterizing channel error, however, is difficult. There are many factors that influence channel performance on any particular day, including factors discussed in the previous paragraph. The 88-10-2 channel model is a simplified solution sufficient for the scope of this research. For future study it may prove to be inadequate. Future work to model the telemetry downlink or improve the performance of the protocol should first enhance the channel BER model to incorporate, for example, the possibly dynamic effects of the environmental-type variables discussed above.

Another area of future work is to further develop the connection between CCSDS configurations and actual DoD mission requirements. Only three mission-oriented priority scenarios were considered: maximize throughput without regard to data quality, maximize data quality without regard to throughput, and maximize both throughput and data quality with equal priority. The world is not usually this simple, nor are telemetry downlink requirements. For this reason there is value to be gained from optimizing the CCSDS protocol for other priority scenarios. This could be as simple as finding the best configuration for a 75:25 priority split, or it could be maximizing other measures of performance, in particular data latency, which will be useful as near-real-time applications continue to grow.

Finally, this research demonstrated the potential for the ATM protocol to meet, and possibly exceed, the performance of the CCSDS protocol in the DoD test range community. Although initially designed to operate on networks with negligible BERs, the ATM protocol performed adequately when BERs were significant. Granted, the evaluation of the protocol in this research work was a simple baseline test. The results were favorable, however, adding justification for further investigation into using the ATM protocol in the test range community. This may gain the DoD interoperability with civilian systems/networks that does not readily exist now.

CHAPTER VI - FLIGHT TEST

6.1 Introduction

This chapter describes the flight test program associated with the research discussed in previous chapters. It summarizes the configuration, execution, data analysis, results, and conclusions of the flight test. Previous chapters describe the modeling and simulation of the CCSDS packet telemetry protocol. The simulations showed a correlation between three specific CCSDS protocol parameters and the resulting throughput and data quality performance of the protocol. The primary purpose of the flight test was to validate these findings and attempt to find an optimal combination of CCSDS parameters to maximize protocol performance based on mission requirements.

Flight testing was conducted from 5 to 31 October 2001, at Edwards AFB, California and supported the ARTM JPO, also located at Edwards AFB. The responsible test organization was the 412th Test Wing located at Edwards AFB. Testing was conducted by the "NEED INFO" test team, United States Air Force Test Pilot School (USAF TPS), Class O1A using a Sabreliner T-39A passenger jet. One airborne equipment/software validation sortie, six data collection sorties, and two backup sorties were flown, for a total of 27 flight hours.

Preliminary results confirmed the correlation between the previously identified CCSDS parameters and the resulting protocol performance. Further testing identified a combination of parameters that would maximize data throughput, data quality, or provide a combined "best of both worlds" solution. The complete flight test report is in [9].

6.2 Test Description

6.2.1 Test Item Description. The test item was the CCSDS packet telemetry protocol. This protocol was discussed at length in Chapters II and III, and will only be summarized here. The three CCSDS protocol parameters identified as strongly influencing the performance of the telemetry system are source packet length, transfer frame length, and Reed-Solomon encoding. The data to be transmitted between sender and receiver is organized into source packets. The source packets used in this study consisted of a six byte header and variable length data field (from 1 to 65,536 bytes). The source packets are then multiplexed together into a synchronous stream of fixed-length transfer frames for transmission to the ground. The transfer frames used in this study consisted of an eight byte header and variable length data field (from 1 to 1107 bytes). During the simulation portion of this research work, the transfer frame header was six bytes. During preparation for the flight test, software upgrades mandated an eight-byte transfer frame header. This did not appear to significantly affect the results.

Reed-Solomon is the optional error correction code capable of correcting up to 16 byte errors in each block of 223 bytes. If used, an additional 160 check bytes are appended to the transfer frame. If not used, an additional 2 bytes of CRC bytes are added to provide a basic error detection capability. Finally, four synchronization bytes are attached and the transfer frame is ready for transmission. Once received on the ground, the process is reversed to retrieve the original data in the source packets.

Another objective of the flight test was to compare the performance of the ATM and CCSDS protocols. ATM technology is a form of packet-switched transmission that uses fixed-sized units, called cells, to transmit data between sender and receiver. Each cell is 53 bytes long; five overhead bytes and 48 bytes of data. This protocol was originally designed for networks with very low BERs.

The two metrics used were throughput and data quality. Throughput is defined as the number of data bytes successfully received by the ground node per unit time (bytes per second). Data quality is defined as the percentage of successfully received source packets at the ground node versus the total number transmitted. This statistic is expressed as a percentage, with 100% indicating error-free data transmission. In both cases, a byte was considered successfully received if it was part of a transfer frame that was successfully received. A transfer frame was successfully received if the number of bytes in error is within allowable error tolerances. The error tolerances depended on whether Reed-Solomon encoding was being used or not. If not used, a transfer frame was considered successfully received if it contained no byte errors. If Reed-Solomon was used, a transfer frame was considered successfully received if the number of bytes errors was less than the number correctable by Reed-Solomon.

6.2.2 Test Objectives. The flight test program had the following four objectives:

- Objective 1: Observe the effects of transfer frame payload length, source packet payload length, and Reed-Solomon encoding on throughput performance of the CCSDS packet telemetry protocol. Determine the optimal combination of these parameters to maximize throughput of error-free data.

- Objective 2: Observe the effects of transfer frame payload length, source packet payload length, and Reed-Solomon encoding on data quality performance of the CCSDS packet telemetry protocol. Determine the optimal combination of these parameters to maximize the percentage of error-free data.

- Objective 3: Determine and demonstrate the combination of transfer frame payload length, source packet payload length, and Reed-Solomon encoding parameters that provides the best compromise between throughput and data quality. Throughput and data quality will be weighted equally during the evaluation.

- Objective 4: Collect data in order to demonstrate the potential performance of the ATM packet protocol in the aeronautical telemetry environment. This will be done by configuring the CCSDS parameters to mimic the data-to-overhead ratio of an ATM cell. Compare the resulting throughput and data quality with the CCSDS performance achieved in Objectives 1-2.

6.2.3 Test Aircraft. The T-39A (S/N 60-3478) test aircraft, a Sabreliner T-39A passenger jet like the one shown in Figure 25, was provided and operated by the 418th Flight Test Squadron. The T-39A aircraft, capable of flying the maneuvers/profiles to fully exercise the CCSDS telemetry protocol, is a low wing, twin-jet, monoplane with axial-flow engines mounted on each side of the aft fuselage. Two equipment racks were installed in the passenger compartment of the T-39A in place of two of the normal passenger seats. The test aircraft provided 28 VDC electrical power to the equipment racks and also locations on the upper and lower fuselage for the required antennas.

Figure 25. T-39A Sabreliner

6.2.4 Test Range. All testing was accomplished in the R-2515 complex at Edwards AFB, California. The ARTM JPO S250 Comm Shelter shown in Figure 26 was used to capture and process the signals transmitted from the test aircraft. The S250 shelter met all telemetry processing requirements and was specially configured for the mission. Normal operational telemetry facilities were not required.

Figure 26. S250 Comm Shelter

6.3 Limitations & Assumptions

6.3.1 Channel BER. Based on previous flight test work by the ARTM JPO, as described in Appendix A (Section A.3), the channel used in the simulations followed a 88%, 10%, 2% breakdown of error-free, cluster error, and burst error periods, respectively. The first sortie in the flight test program was dedicated to choosing a location for the racetrack flight path that would roughly achieve a similar channel BER. It quickly became evident that this would be difficult as even the most error-prone locations on Edwards AFB were producing only a few percent of total error. This is attributed to new antenna/receiver equipment installed after the channel characterization work that was the basis for the channel modeling used in the OPNET simulations. Rather than use the "better" channel for the flight test, it was decided to install an attenuator on the receiver in order to artificially worsen the channel and attempt to get closer to the desired 88-10-2 breakdown of errors. The actual breakdown achieved was roughly 95-4-1. This was accomplished using a 40 dB attenuator; attenuating the signal greater than that caused the noise level to start masking the signal. The decision to degrade the channel was made for two reasons. First, the results would be easier to compare with the modeling and simulation results. In other words, channel BER is assumed not to be a significant variable in the experiment. Actually, there was some variance between the experimental and flight test BERs. The second reason is that the larger BER made it easier to illustrate the benefits and drawbacks due to each CCSDS parameter configuration. This was particularly the case when demonstrating the advantages/disadvantages of Reed-Solomon encoding, namely, with few errors to correct, the performance gained using Reed-Solomon was insignificant. The larger BER made it possible to clearly distinguish the advantages of various configurations.

6.3.2 Software Restrictions on Transfer Frame Length. According to the CCSDS Blue Book [4,5], transfer frame length can take on any value up to 1115 bytes whether Reed-Solomon encoding is used or not. The Avtec software implementation [3] used by the ARTM JPO, restricted transfer frame length to a single value of 939 bytes if Reed-Solomon encoding was ON, but let it take on any value up to 1115 bytes if Reed-Solomon encoding was OFF. This was intentionally done by the software programmers to maximize the data-to-overhead ratio of the transfer frame when 160 bytes of overhead are added due to Reed-Solomon encoding. In the simulation model (c.f., Chapters III and IV), transfer frame length was not restricted when Reed-Solomon was ON. As will be shown below, this did not significantly affect the results with regard to throughput performance. However, with respect to data quality, some discrepancies between the experimental and flight test results were noted. These are discussed further in Section 6.6.

6.3.3 Software/Hardware Limitations. All "events" in the telemetry downlink process resulted in an interrupt in the computer software/hardware executing the CCSDS packet protocol implementation. "Events" include generation of frames and packets, transmission of frames, and receipt of frames. One event that generates a large number of interrupts is the creation of source packets. The smaller the size of the source packet, the more frequently interrupts occurred. As source packet size was decreased, there was a point where the software/hardware could no longer keep up with the interrupts and the computer would crash. Therefore, the smallest source packet payload length tested was 30 bytes. The smallest transfer frame payload length in the test matrix, 50 bytes, did not result in interrupt problems.

6.4 Flight Test Execution

A total of 61 test points were flown and data was collected to determine the effects of transfer frame length, source packet length, and Reed-Solomon encoding on data quality. The test points are listed in Table 8 below. For each test point, the telemetry system was configured to transmit a known data stream to the ground station and the test aircraft flew a predetermined, twelve (12) minute racetrack pattern at 4500 ± 50 feet mean sea level (MSL) over CORDS Road in the R-2515 Edwards AFB test area. The racetrack pattern is illustrated in Figure 27. After test completion, the known stream was compared to the data stream received at the ground station.

6.5 Post-Flight Data Processing

A pre-determined test sequence was transmitted from the aircraft during each pass through the route. The chosen route exposed the telemetry data stream to both "error-free" and "error-prone" areas to evaluate the robustness of the CCSDS protocol. The transmitted stream was recorded to CD-R media, as was the stream that was ultimately received at the ground comm-shelter. Also recorded was the total transmission time. Transmission time is defined as the time from the transmission of the first byte to the last byte during each pass around the route (one pass = one data point). At the completion of

Table 8. Flight Test Data Points

Run	TF Len (bytes)	SP Len (bytes)	RS
1	50	30	N
2	50	194	N
3	50	500	N
4	50	2000	N
5	50	20000	N
6	50	60000	N
7	200	30	N
8	200	194	N
9	200	500	N
10	200	2000	N
11	200	20000	N
12	200	60000	N
13	400	30	N
14	400	194	N
15	400	500	N
16	400	2000	N
17	400	20000	N
18	400	60000	N
19	600	30	N
20	600	194	N
21	600	500	N
22	600	2000	N
23	600	20000	N
24	600	60000	N
25	800	30	N
26	800	194	N
27	800	500	N
28	800	2000	N
29	800	20000	N
30	800	60000	N

Run	TF Len (bytes)	SP Len (bytes)	RS
31	1000	30	N
32	1000	194	N
33	1000	500	N
34	1000	2000	N
35	1000	20000	N
36	1000	60000	N
37	198	192	N
38	939	30	Y
39	939	194	Y
40	939	500	Y
41	939	2000	Y
42	939	20000	Y
43	939	60000	Y
44	125	30	N
45	125	194	N
46	125	500	N
47	125	2000	N
48	125	20000	N
49	125	60000	N
50	300	100	N
51	300	350	N
52	300	750	N
53	300	1000	N
54	300	5000	N
55	300	40000	N
56	500	100	N
57	500	350	N
58	500	750	N
59	500	1000	N
60	500	5000	N
61	500	40000	N

each flight, this data was reduced to produce the metrics for the corresponding objective(s). Data reduction consisted of comparing the sent and received streams with the goal of determining the number of source packets and ultimately the number of data bytes successfully received. An in-house software program written by the ARTM JPO was used to facilitate a byte-wise comparison of the transmitted and received stream to

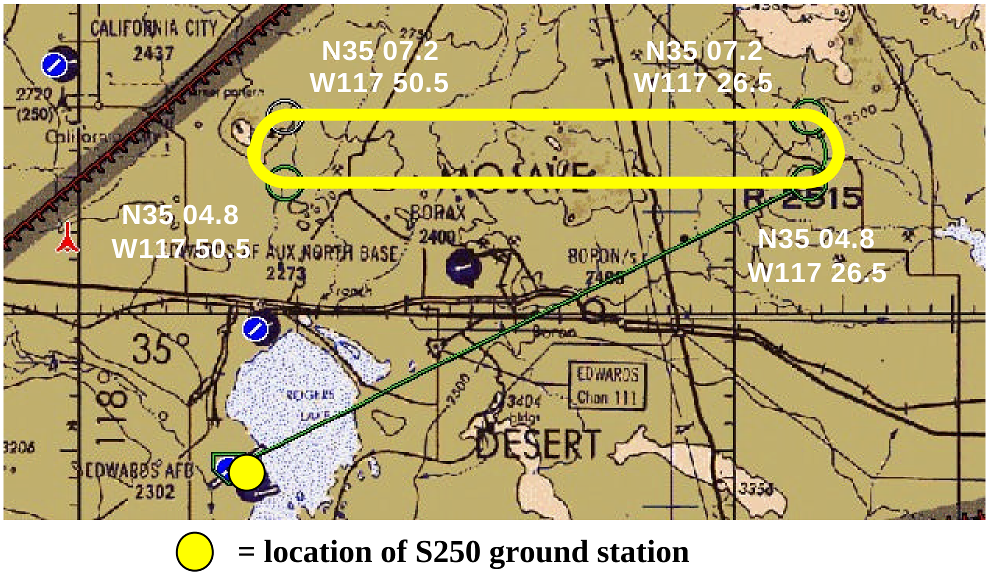


Figure 27. Racetrack Route

determine the number of successfully received source packets. The number of data bytes successfully received was calculated by multiplying the number of successfully received source packets by the length of a source packet data payload (in bytes). Source packet payload length was constant during each data point.

Analysis of the data and results obtained in Objectives 1 and 2 was performed by two methods. The first method was an analysis of variation (ANOVA) with the combined maximization of throughput and data quality as the desired output. The second method was inspection of processed data in the form of a contour plot illustrating the overall variation of the dependent variables with respect to the independent variables on a single chart. In both methods, throughput and data quality were equally desirable in the evaluation.

The following equation was used to calculate throughput:

$$\text{Throughput} = \frac{\#\ \text{error free bytes received}}{\text{total transmission time (sec)}}$$

The following equation was used to calculate data quality:

$$\text{Data Quality} = \frac{\#\ \text{source packets successfully received}}{\text{total number of source packets sent}} \text{ x } 100$$

The goal of Objective 4 was to demonstrate the potential performance of the ATM packet protocol in the Department of Defense aeronautical telemetry environment. This was done by configuring the CCSDS parameters to mimic the data-to-overhead ratio of an ATM cell, and comparing the optimum throughput and data quality performance of both protocols. For the CCSDS case, the maximum simultaneously achievable throughput and data quality, as determined in Objective 3, was used for the comparison. Throughput and data quality values used for the ATM protocol were the arithmetic mean of data obtained on two data runs.

6.6 Flight Test Experimental Results and Analysis

6.6.1 Objective 1. As shown in Figure 28, effective throughput was dependent on transfer frame length. Figure 28 through Figure 31 show selected data to illustrate trends in tested parameters. Tables and plots of collected data are in Appendix F. In general, throughput increased as transfer frame length was increased until transfer frame payload length reached 800 bytes, where throughput began to drop off. Further testing may be able to locate a more precise peak. This information may be of value if mission objectives necessitate the transmission of data with minimum delay but with some flexibility with regards to loss of data. Given that the collected data has only a small spread, the benefit in finding a precise peak is likely not worth the time and resources to find it.

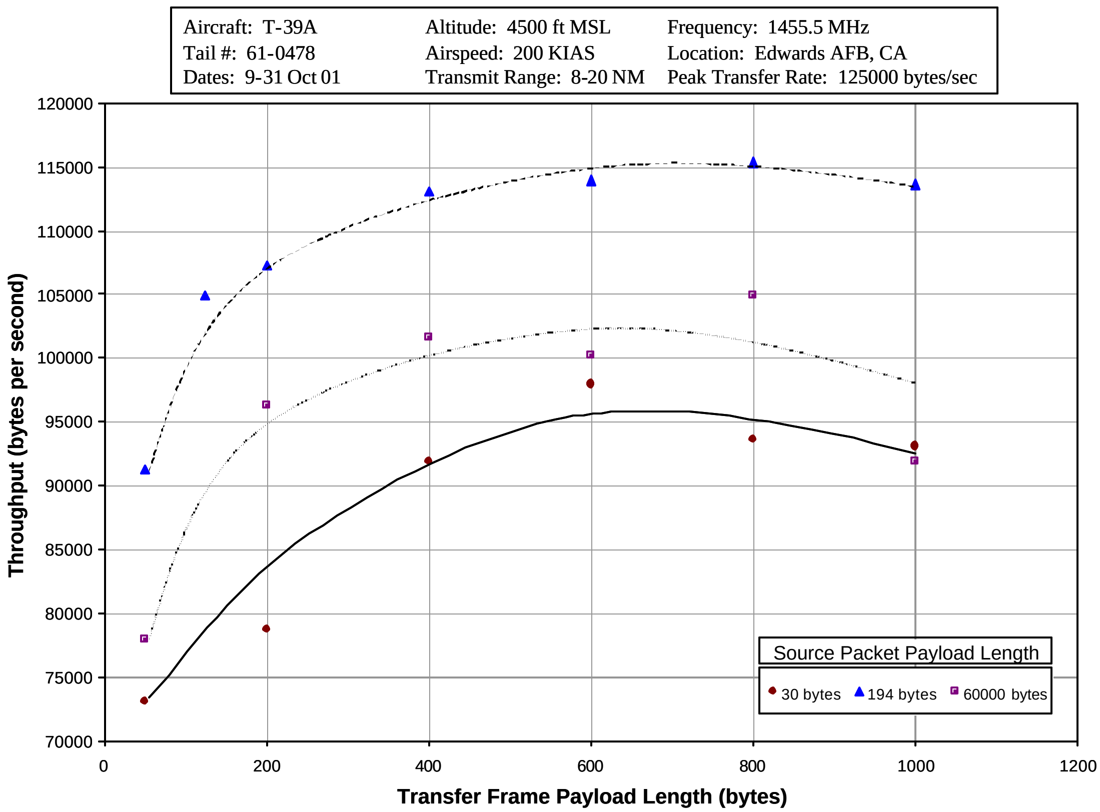


Figure 28: Throughput Variation with Transfer Frame Payload Length

(Trendlines shown are hand-drawn)

As Figure 29 shows, effective throughput is also dependent on source packet length. Throughput performance was the highest for source packet lengths between 200 and 2000, but decreased for source packet lengths below 200 and above 2000 bytes. A source packet length of 500 bytes consistently produced the best throughput performance. Further testing may be able to locate a more precise peak, however, given there is only a 2% difference between the high and low throughput values in the 200 to 2000 byte source packet range, the benefit gained in finding a precise peak is again likely not worth the effort.

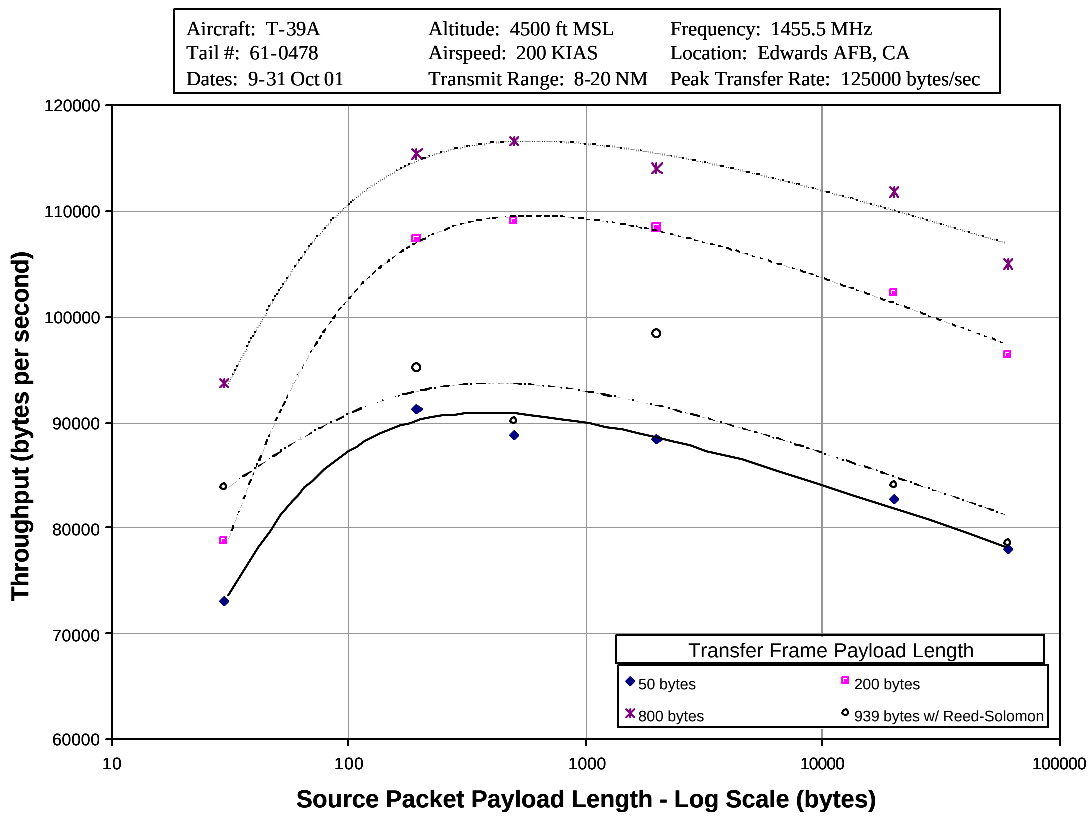


Figure 29: Throughput Variation with Source Packet Payload Length

(Trendlines shown are hand-drawn)

Figure 29 also shows the effect of Reed-Solomon encoding on throughput performance. In general, throughput performance followed the same trend as the non-Reed-Solomon cases, however throughput performance overall was lower with the exception of the 50 byte transfer frame length case. With Reed-Solomon encoding ON, the highest throughput was 97,931 Bps (at source packet length of 2000). This is 16% lower than the maximum achievable throughput with Reed-Solomon encoding turned OFF. The data point at source packet length of 500 bytes fell outside the general trendline and may have been an outlier. This point was not reflown due to flying time constraints, however using a statistical software package, the predicted throughput for that source packet length is 99017 Bps. Using this predicted value, throughput performance is still 15% below the maximum achievable with Reed-Solomon OFF. Therefore, the test team concluded that Reed-Solomon encoding should be off for maximum throughput performance.

As noted earlier, the Avtec software implementation [3] used by the ARTM JPO restricted transfer frame length to a single value (939 bytes) if Reed-Solomon encoding was ON, but let it take on any value up to 1115 bytes if Reed-Solomon encoding was OFF. In the modeling and simulation work done in conjunction with this flight test, transfer frame length was not restricted when Reed-Solomon was ON. However, the results of that work were not significantly different than the results demonstrated during the flight test and do not require further investigation with regards to throughput performance.

The configuration of CCSDS parameters that yielded the best throughput performance was a transfer frame length of 800 bytes, source packet length of 500 bytes, and Reed-Solomon encoding OFF. This solution yielded an overall throughput of 116,551 Bps. Given that the worst-case 99% confidence interval on the throughput data collected was ±1877 Bps, throughput values reported are estimated to be accurate to within ±1.6%. Analysis of variance (ANOVA) [8] on the data showed that transfer frame length contributed 41.3% to the resulting throughput, source packet length 36%, and Reed-Solomon encoding 12%. The remaining 11% was due to the interaction between transfer frame and source packet length. It was therefore concluded that a transfer frame length of 800 bytes, source packet length of 500 bytes, and Reed-Solomon encoding off should be used to obtain maximum throughput.

The flight test results generally agree with the simulation conclusions. The simulation results suggested that throughput could be maximized using a transfer frame payload length in the range 600-1000 bytes, a source packet payload length in the range 500-2000 bytes, and Reed-Solomon encoding OFF. The configuration that yielded the best throughput performance during the flight test fell within these bounds. Both sets of results found similar trends and relationships between the protocol parameters and the resulting throughput. With regard to transfer frame length, throughput continued to increase through the entire range during the simulation (i.e., for TF = 1000), whereas during the flight test throughput started to decrease after 800 bytes. This is most likely due to the differences between the test model and actual flight test conditions. As for source packet length, both the simulation and flight test narrowed in on a similar range of possible source packet lengths, 500-2000 bytes and 200-2000 bytes, respectively. Both the simulation and flight test results clearly demonstrated the advantages of not using Reed-Solomon encoding to maximize throughput. A final difference in results was the configuration that achieved maximum throughput: (TF = 1000, SP = 1000, RS OFF) from the simulation results versus (TF = 800, SP = 500, RS OFF) from the flight test results. This discrepancy, however, is insignificant and is most likely due to differences between the test model and actual flight test conditions.

6.6.2 Objective 2. Figure 30 shows the effect of transfer frame length on data quality. As predicted, the data demonstrated that there was little correlation between transfer frame length and data quality and no specific trends were drawn from the data. An ANOVA of the data concluded that transfer frame length contributed to 6.8% of the data quality. The ANOVA also indicated an interaction between source packet and transfer frame length contributing to 24% of the data quality, although the test team was unable to determine the specific reason for the interaction.

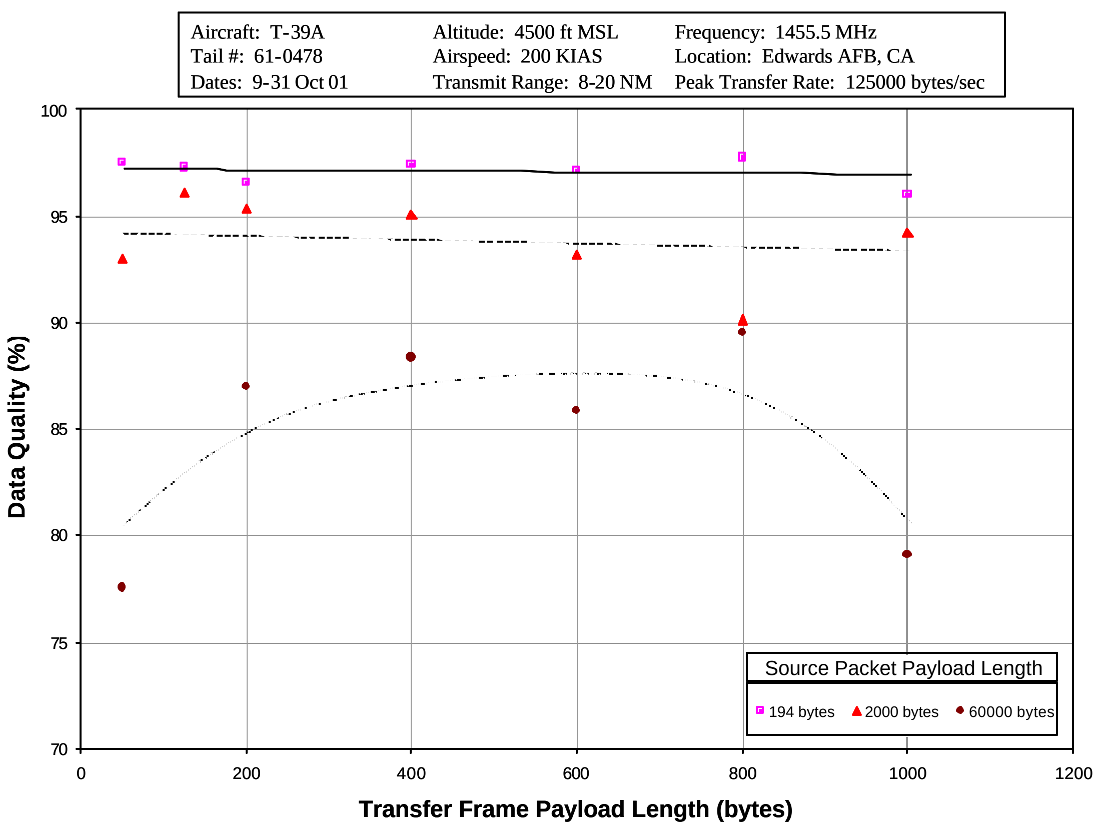


Figure 30: Data Quality Variation with Transfer Frame Payload Length

(Trendlines shown are hand-drawn)

Figure 31 shows the effect of source packet payload length on data quality, with the payload length given on a logarithmic scale. As predicted, the data quality decreased as source packet length increased with a maximum average data quality of 97.1% occurring with a source packet length of 194 bytes. Flight test data also showed that data quality for source packet lengths of 30 bytes aggregated into two groups, one having a data quality 5% lower. This may be due to the specific hardware implementation used and limits on producing very small source packets at rapid rates. An ANOVA evaluation of the flight test data concluded that source packet length contributed up to 65% to data quality.

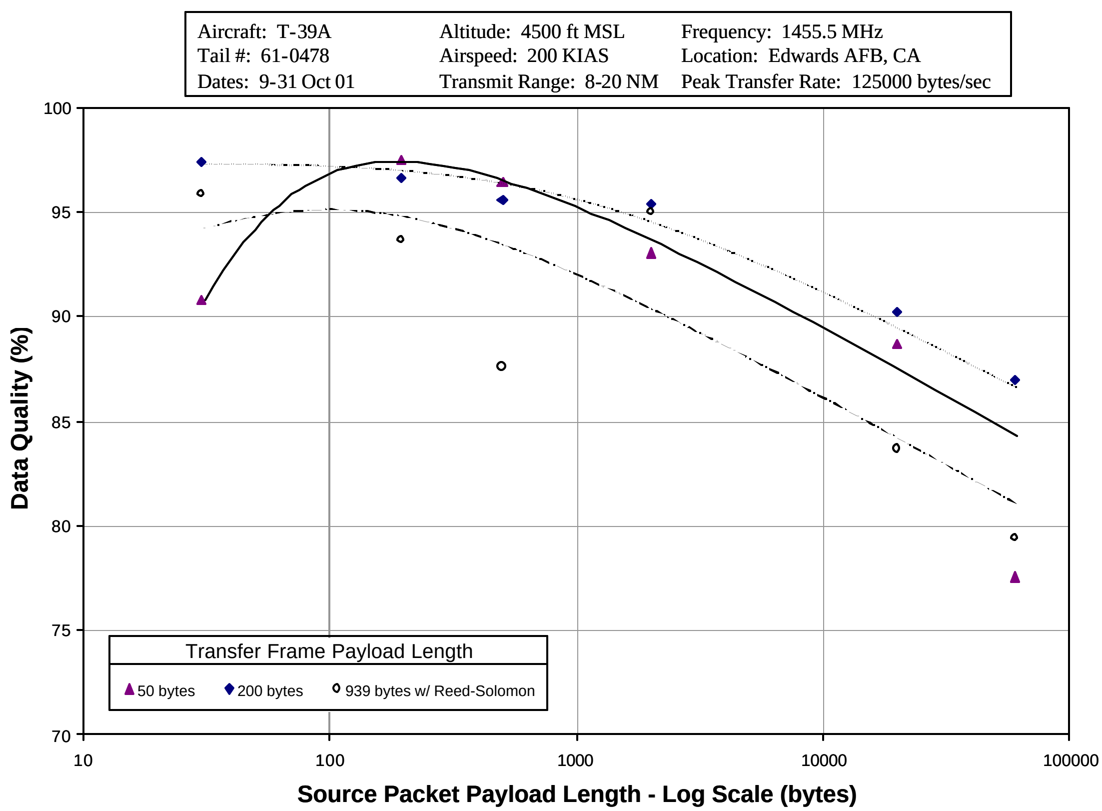


Figure 31: Data Quality Variation with Source Packet Payload Length

(Trendlines shown are hand-drawn)

Due to restrictions imposed by the CCSDS implementation software, Reed-Solomon encoding could only be tested with a transfer frame payload length of 939 bytes (1119 bytes total transfer frame length). The collected data indicated that Reed-Solomon encoding may decrease data quality, rather than increasing it as was predicted by the modeling and simulation work. An ANOVA of the data generated a negligible contribution (0.02%), indicating that the effect of RS encoding is probably insignificant for the tested configurations. However, the absence of data at multiple transfer frame lengths prevented a more in-depth evaluation concerning the use of Reed-Solomon encoding. It was therefore concluded that the effects of Reed-Solomon encoding on data quality with the transfer frame length restriction removed should be investigated.

The configuration of CCSDS parameters that yielded the best data quality was a source packet payload length of 194 bytes with no Reed-Solomon encoding. This configuration yielded an average data quality of 97.1%. It was therefore concluded that a source packet length of 194 bytes with Reed-Solomon encoding off should be used to obtain maximum data quality.

There is some discrepancy between the simulation and the flight test data quality results. Both agreed that transfer frame length is not a factor in determining data quality. Both found a similar relationship between packet length and data quality. The range of source packet payload lengths identified to maximize data quality differed, however: 500-2000 bytes from the simulations versus 194 bytes from the flight test results. The simulations identified a very slight advantage to using Reed-Solomon whereas the flight tests did not. There are a couple of items to note about these differences. First, Reed-Solomon testing during the flight test was limited due to software restrictions on transfer frame length. Granted, it was concluded that transfer frame length does not play a role in determining data quality; nonetheless, it limited the amount of data collected with Reed-Solomon ON. Second, the advantage of using Reed-Solomon identified in the simulations was less than 2% in terms of throughput. Given better channel conditions, the advantages of Reed-Solomon would be even smaller. Finally, considering source packet lengths can range from 7 bytes to over 65,000 bytes, the differences in source packet ranges are not that significant and are most likely due to differences between the model and actual flight test conditions.

6.6.3 Objective 3. As indicated from the results of Objectives 1 and 2, Reed-Solomon encoding OFF resulted in a significant improvement in throughput and had little effect on data quality within the limited parameters tested. Analysis of the combined results indicated that the optimum combination of throughput and data quality was achieved with Reed-Solomon encoding OFF, as well.

Both the ANOVA and the contour plot (Figure 32) suggest that the best throughput and data quality combination occurs with a transfer frame length of 800 bytes and a source packet length of 500 bytes. Since Objective 2 results indicated that data quality did not vary significantly with transfer frame length, the fact that the best combined performance occurred at the transfer frame length for optimum throughput was expected. However, the reason that the source packet length for optimum throughput matched that for best combined performance was less obvious, until observing the contour plot. Recall that the source packet length for optimum data quality was 194 bytes. Figure 32[8] illustrates that in the area corresponding to a transfer frame length of 800 bytes and source packet lengths between approximately 200 and 500 bytes, the slope of data quality results are extremely shallow when compared to those of throughput results. This indicates that changing source packet length from 194 bytes to 500 bytes would have very little effect on data quality but could noticeably improve throughput. It was therefore concluded that a transfer frame length of 800 bytes and source packet length of 500 bytes with Reed-Solomon encoding off should be used to obtain an optimum combination of throughput and data quality.

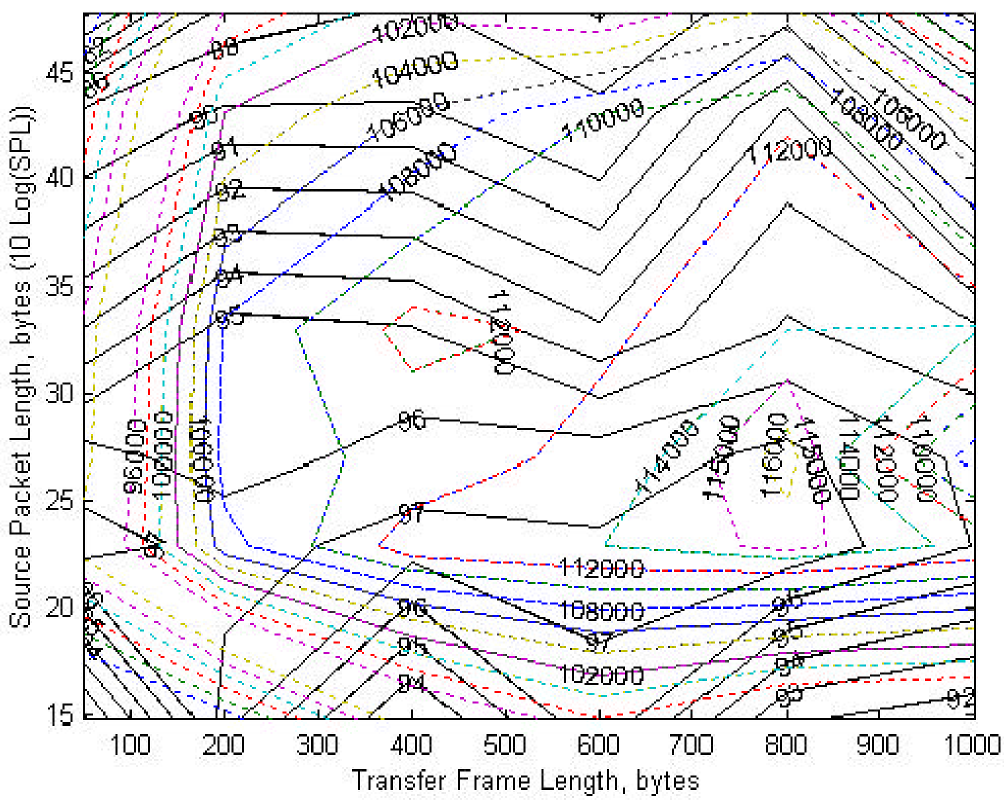
6.6.4 Objective 4. Table 9 shows the results of the CCSDS / ATM protocol comparison[9]. Overall, these results agreed with the results of the modeling and simulation. One item of note is that the CCSDS equivalent configuration was (TF = 198 bytes, SP = 192 bytes) versus (TF = 179 bytes, SP = 173 bytes) used in the simulations. This was due to the increase in size of the transfer frame header to 8 bytes due to requirements by the Avtec software used to implement the CCSDS protocol.

Data quality between the two protocols was not significantly different (0.21% decrease using ATM). This was well within the error margins of the data and also consistent with predictions (see Table 6). Throughput performance was 6.47% higher using CCSDS. This difference could be partially accounted for by error margins in the data, or condition variations on the days the test points were flown. It was not determined significant enough to discourage further study of the ATM protocal for DoD

[8] In Figure 32, four data points were discarded due to noise in the TM signal. These points were replaced with a linear interpolation of adjacent points.
[9] A sample size of two yielded a confidence level of 80%. Throughput data is accurate to within ±1930 Bps. Data quality data is accurate to within ±1.57 percentage points.

test & evalutation, especially when considering the potential benefits of civilian sector interoperability. Overall, data quality and throughput performance using the ATM protocol was sufficiently close to that of CCSDS. These results demonstrate cause for further study of the ATM protocol for DoD test and evaluation telemetry needs. An ATM airborne testbed using ATM-specific equipment would adequately display the capabilities of the protocol. It was therefore concluded that further exploration of using the ATM protocol in the DoD test environment should be accomplished.

Aircraft: T-39A	Altitude: 4500 ft MSL	Frequency: 1455.5 MHz
Tail #: 61-0478	Airspeed: 200 KIAS	Location: Edwards AFB, CA
Dates: 9-31 Oct 01	Transmit Range: 8-20 NM	Peak Transfer Rate: 125000 bytes/sec



Legend: - - - - - - - Throughput (bytes/sec)
———— Data Quality (%, quality data received/sent x 100)

*Note: Plot based on raw data, absent of four outliers. Outliers replaced with a linear interpolation between adjacent points.

Figure 32: Contour Plot of Flight Test Data

Table 9. Flight Test CCSDS/ATM Protocol Performance Comparison

Protocol	Transfer Frame Payload Length (Bytes)	Source Packet Payload Length (Bytes)	Data Quality (%)	Throughput (Bps)
CCSDS	800	500	97.1	115,357
ATM	198	192	96.9	107,899
		Percent Difference =	-0.21%	-6.47%

6.7 Reconfiguration of Simulation Model to Match Flight Test Conditions

During the execution of the flight test, the channel was characterized by approximately 95% error-free behavior, 4% cluster-error behavior, and 1% burst-error behavior. This was significantly different from the simulation channel model, which was characterized by approximately 88% error-free behavior, 10% cluster-error behavior, and 2% burst-error behavior. In most cases, the simulation and flight-test results matched despite the differences in channel behavior, however to further assess the effects of the channel BER on CCSDS performance, the simulation channel model was reconfigured to follow the 95-4-1 breakdown of error. In addition, transfer frame header size was increased by two bytes, as was the case during flight test due to Avtec software requirements. The initial 73 test cases, plus 24 secondary test cases, were rerun using the modified model. The secondary test cases were again necessary to further define the relationship between source packet length and data quality. For the most part, the new simulation results supported the conclusions made after the first simulation sequence using the 88-10-2 channel model[10]. The results also shed light on the possible significance of environmental variables, such as atmospheric effects and antenna

[10] A sample size of five yielded a worst-case confidence level of 90%. Throughput data is accurate to within ±127 Bps. Data quality data is accurate to within ±0.103 percentage points.

position, in the telemetry downlink. A summary of the results of the second simulation sequence is presented in this section. The throughput and data quality results in their entirety are provided in Appendix G.

With regards to throughput, the results using the 95-4-1 channel model were no different than during the simulation sequence using the 88-10-2 channel model. Throughput again increased as transfer frame length increased. A transfer frame payload length of 1000 bytes produced the highest throughput, with payload lengths between 600 and 1000 bytes again producing near-maximum performance. Source packet payload lengths between 500 and 6000 bytes produced the best throughput performance, which was generally in agreement with the results of the previous simulation results. The wider range of possible source packet lengths is consistent with the improvement in the channel BER. During the flight test, throughput began to drop off around a source packet payload length of 2000 bytes, whereas in the 95-4-1 simulation, throughput was high up to a source packet payload length of 6000 bytes. The difference is most likely due to the environmental type errors that existed in the Edwards test range, but were not explicitly included in the simulation model. With a "cleaner" channel in the simulator, longer source packets were able to successfully navigate the channel. A source packet payload length of 2000 bytes consistently produced the highest data throughput in the 95-4-1 simulations, and Reed-Solomon OFF was, again, clearly more advantageous.

Analysis of data quality performance using the reconfigured channel model again showed little correlation between transfer frame length and the resulting data quality. Source packet payload lengths between 500 and 6000 bytes produced the best data quality performance. This was similar to the results of the simulation runs using the 88-

10-2 channel model. A payload length of 1000-2000 bytes consistently produced the highest data quality. Again, the wider range of possible source packet lengths is consistent with the improvement in the channel BER. As seen in prior simulation results, there was a slight improvement in data quality with Reed-Solomon ON, although the improvement was less than 1.4%. This is demonstrated in Figure 33. Using the 88-10-2 simulation model, the improvement in data quality with Reed-Solomon ON was up to 2%. As expected, the advantages gained by Reed-Solomon decreased as the channel improved. Analysis of the flight test data showed that data quality actually decreased by up to 4.4% (the average decrease was less than 3%) with Reed-Solomon ON. The difference between the simulation and the flight test results is most likely due to dynamic elements in the test range environment and flight test conditions that were not explicitly incorporated into the simulation channel model, such as antenna patterns and aircraft movement relative to the ground station. The simulation and flight test results suggest that any advantage gained by turning Reed-Solomon ON is small, and turning it ON could actually decrease data quality as was the case during the flight testing at Edwards AFB.

Using the method of analysis used previously with the 88-10-2 simulation model, the 95-4-1 simulation data suggests that to achieve the best combined throughput and data quality, transfer frame payload length should be between 600-1000 bytes, source packet payload length should be from 500 - 6000 bytes, and Reed-Solomon OFF. Figure 34 shows a contour plot of the throughput and data quality results from the 95-4-1 simulation model overlaid. As with previous analysis of both simulation and flight test data, the configuration yielding the best compromise was also the configuration yielding the best throughput performance.

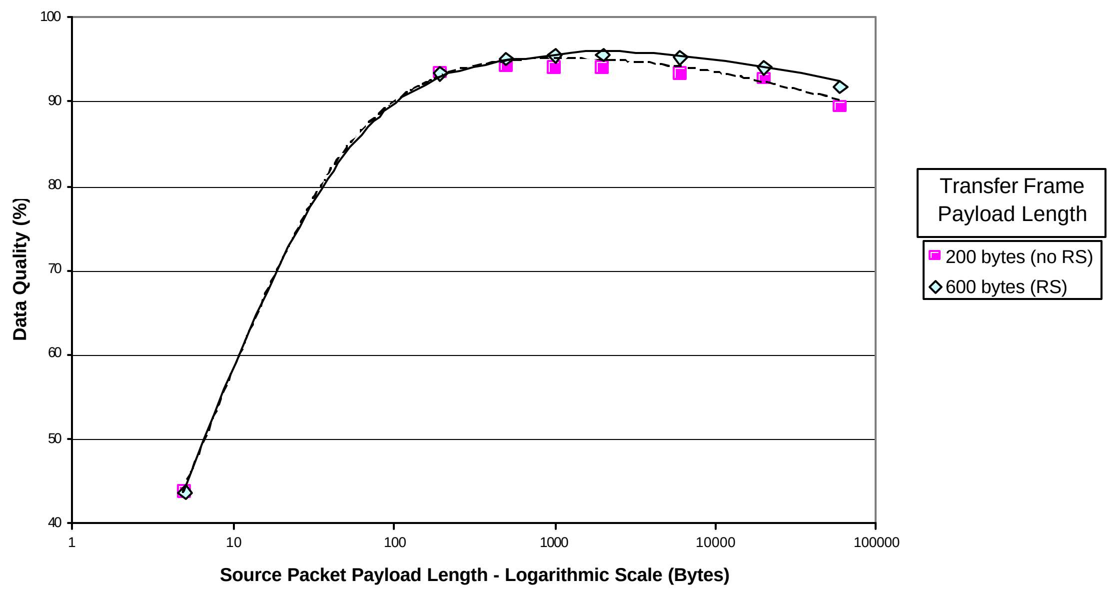


Figure 33. Effects of Reed-Solomon on Data Quality Using 95-4-1 Simulation Model

(Trendlines shown are hand-drawn)

Table 10 shows how the "ATM-version" of CCSDS faired in comparison to the best performance of the CCSDS protocol in the 95-4-1 simulation model. Due to the increase in transfer frame header size, the CCSDS configuration used in the "ATM-version" was a transfer frame payload length of 198 bytes, a source packet payload length of 192 bytes, and Reed-Solomon encoding OFF. The CCSDS configuration used for the comparison was a transfer frame payload length of 1000 bytes, a source packet payload Length of 2000 bytes, and Reed-Solomon encoding OFF. This configuration was chosen because it produced the best compromise between throughput and data quality in the 95-4-1 simulation model. These results are similar to those obtained during the 88-10-2 simulation sequence and the flight test. Again, these results suggest further exploration of using ATM, or an ATM-CCSDS hybrid, in the DoD test range community.

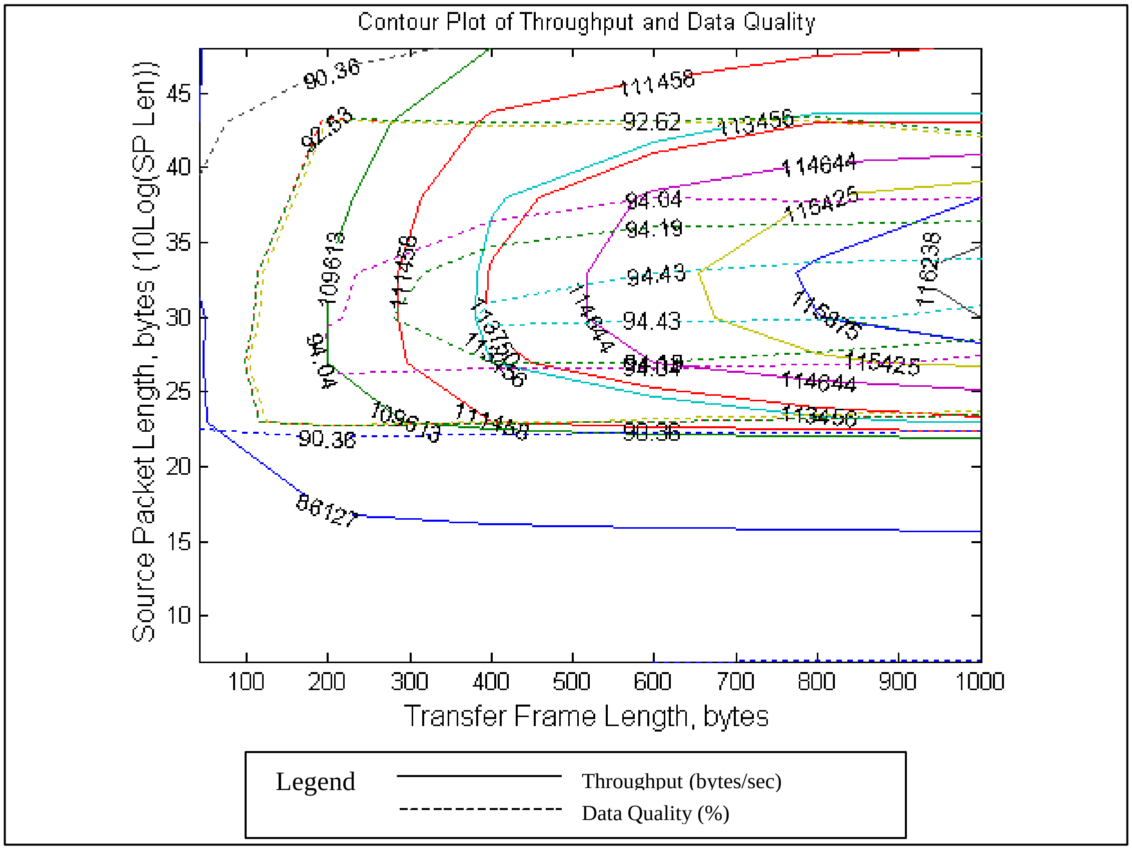


Figure 34. Contour Plot of Combined Performance Using the 95-4-1 Channel Model

Table 10. Comparison of ATM and CCSDS Using the 95-4-1 Simulation Model

Protocol	Transfer Frame Payload Length (Bytes)	Source Packet Payload Length (Bytes)	Data Quality (%)	Throughput (Bps)
CCSDS	1000	2000	94.48	116,610
ATM	198	192	93.37	107,890
		Percent Difference =	-1.17%	-7.48%

6.8 Flight Test Conclusions and Recommendations

The Consultative Committee for Space Data Systems (CCSDS) packet telemetry recommendation was successfully evaluated for use in the Department of Defense (DoD) test range environment. The effect of transfer frame length, source packet length, and Reed-Solomon encoding on throughput and data quality were determined. In general, test results agreed with simulation model predictions. In addition, sufficient data was collected to compare CCSDS and ATM performance. All objectives were met.

Effective throughput is dependent on transfer frame length, source packet length, and Reed-Solomon encoding. In general, throughput increased with transfer frame length until a transfer frame length of 800 bytes, at which point throughput began to drop off. Throughput performance was the highest for source packet payload lengths between 200 and 2000 bytes, but fell off for payload lengths below 200 bytes and above 2000 bytes. Throughput performance overall was lower when Reed-Solomon encoding was used. The configuration of CCSDS parameters that yielded the best throughput performance was a transfer frame length of 800 bytes, source packet length of 500 bytes, and Reed-Solomon encoding OFF.

1. Reed-Solomon encoding should be off for maximum throughput performance.

2. A transfer frame length of 800 bytes, source packet length of 500 bytes, and Reed-Solomon encoding off should be used to obtain maximum throughput.

Data quality was dependent on source packet length and Reed-Solomon encoding. The data collected demonstrated negligible correlation between transfer frame length and data quality. Data quality decreased with increasing source packet length, with a maximum average data quality of 97.1% occurring at 194 bytes. Due to limitations imposed by the CCSDS implementation software, Reed-Solomon encoding was only tested with a transfer frame payload length of 939 bytes. The collected data indicated that Reed-Solomon encoding may decrease data quality, rather than increasing it as predicted by modeling and simulation. This restriction precluded an in-depth evaluation of the effects of Reed-Solomon encoding on data quality.

3. Effects of Reed-Solomon encoding on data quality with the transfer frame length restriction removed should be investigated.

4. A source packet length of 194 bytes with Reed-Solomon encoding off should be used to obtain maximum data quality.

Both the ANOVA and contour plot analysis suggested that the best throughput and data quality combination occurred with a transfer frame length of 800 bytes and source packet length of 500 bytes. Analysis of the combined data indicated that the optimum combination was achieved with Reed-Solomon encoding OFF.

5. A transfer frame length of 800 bytes and source packet length of 500 bytes with Reed-Solomon encoding off should be used to obtain an optimum combination of throughput and data quality.

CCSDS and ATM protocol performance was compared. Overall, data quality and throughput performance using the ATM protocol was sufficiently close to that of

CCSDS. Data quality between the two protocols was not significantly different. Throughput performance was 6.47% higher using CCSDS.

6. Further exploration of using the ATM protocol in the DoD test environment should be accomplished.

Results of the flight testing are summarized in Table 11 below.

Table 11. Summary of Flight Test Results

Priority Level of Mission Requirements		Reed-Solomon (on/off)	TF Payload Length (Bytes)	SP Payload Length (Bytes)	Best Performing Configuration
Throughput	Data Quality				
100%	0%	ON	Not Recommended		RS: OFF TF: 800 SP: 500
		OFF	800	200 - 2000	
50%	50%	ON	Not Recommended		RS: NO TF: 800 SP: 500
		OFF	800	200 - 500	
0%	100%	ON	Not Recommended		RS: OFF TF: 800 SP: 194
		OFF	Any	194	

CHAPTER VII - OVERALL CONCLUSIONS & RECOMMENDATIONS

7.1 Conclusions

This research evaluated the practical use of the CCSDS packet telemetry protocol in the DoD test range environment and established general guidance for maximizing the performance of the protocol according to mission requirements. Following successful simulation and analysis using network simulation software and a synthesized channel model based on previous flight test results, the CCSDS protocol was evaluated and the simulation results validated during flight test at Edwards AFB, CA. Finally the simulation channel model was modified to more accurately duplicate the channel error encountered during flight test. Using this updated model, the simulations were rerun in an attempt to remove channel BER as a variable differentiating the flight test and simulation results. Table 12 and Table 13 below summarize the overall results of this work.

The flight test results generally agreed with the modeling and simulation results. With regards to throughput, both the simulation and flight test results indicated that throughput generally increases as transfer frame length increases, and that Reed-Solomon should be OFF to achieve higher throughput rates. This intuitively makes sense since a higher data-to-overhead ratio should produce higher throughput rates.

Along the same lines, the better the channel (i.e., lower BER), the greater the number and size of source packets that should be able to successfully make it through the channel. The more that make it through, the higher the resulting throughput should be.

Table 12. Overall Summary of Research Results

Priority Level of Mission Rqmts		Simulation (88-10-2 Channel Model)[11]				Flight Test[12]				Simulation (95-4-1 Channel Model)[13]			
Through-put	Data Quality	RS	TF Payload Length (Bytes)	SP Payload Length (Bytes)	Best Performing Configurations	RS	TF Payload Length (Bytes)	SP Payload Length (Bytes)	Best Performing Configurations	RS	TF Payload Length (Bytes)	SP Payload Length (Bytes)	Best Performing Configurations
100%	0%	ON	Not Recommended		RS: OFF TF: 1000 SP: 1000	ON	Not Recommended		RS: OFF TF: 800 SP: 500	ON	Not Recommended		RS: OFF TF: 1000 SP: 2000
		OFF	600 - 1000	500 - 2000		OFF	800	200 - 2000		OFF	600 - 1000	500 - 6000	
50%	50%	ON	Not Recommended		RS: OFF TF: 1000 SP: 1000	ON	Not Recommended		RS: OFF TF: 800 SP: 500	ON	Not Recommended		RS: OFF TF: 1000 SP: 2000
		OFF	600 - 1000	500 - 1400		OFF	800	200 - 500		OFF	600 - 1000	500 - 6000	
0%	100%	ON	Any	500 - 2000	RS: ON TF: 1000 SP: 1400 / RS: OFF TF: 1000 SP: 1000	ON	Not Recommended		RS: OFF TF: 800 SP: 194	ON	Any	500 - 6000	RS: ON TF: 1000 SP: 2000 / RS: OFF TF: 1000 SP: 2000
		OFF	Any	500 - 2000		OFF	Any	194		OFF	Any	500 - 6000	

[11] Data quality and throughput values based on a channel profile of approximately 88% error-free activity, 10% cluster-error activity, and 2% burst-error activity

[12] Data quality and throughput values based on a channel profile of approximately 95% error-free activity, 4% cluster-error activity, and 1% burst-error activity

[13] Data quality and throughput values based on a channel profile of approximately 95% error-free activity, 4% cluster-error activity, and 1% burst-error activity

Table 13. Overall Results of ATM/CCSDS Comparison

Protocol	Simulation (88-10-2 Channel Model)[14] Data Quality (%)	Simulation (88-10-2 Channel Model)[14] Throughput (Bps)	Flight Test[15] Data Quality (%)	Flight Test[15] Throughput (Bps)	Simulation (95-4-1 Channel Model)[16] Data Quality (%)	Simulation (95-4-1 Channel Model)[16] Throughput (Bps)
CCSDS	87.83	108,360.00	97.1	115,357	94.48	116,610
ATM	87.70	101,572.76	96.9	107,899	93.37	107,890
Percent Difference =	-0.15%	-6.26%	-0.21%	-6.47%	-1.17%	-7.48%

The simulation and flight test results corroborated this hypothesis. In the worst channel (i.e., highest BER) tested, the 88-10-2 simulation model, throughput was highest for source packet payload lengths in the range of 500 to 2000 bytes. The next best channel tested was the test range at Edwards AFB, where the channel followed an approximate 95-4-1 error breakdown but also included dynamic elements of error due to atmosphere, weather, antenna patterns, etc. As expected, data from testing in this channel indicated that throughput was the highest for a slightly wider range of source packet lengths, namely 200 to 2000 bytes. Finally in the channel model that was the best (i.e., lowest BER), the 95-4-1 simulation model, where the dynamic elements of error were not explicitly included, the range of source packet payload lengths producing the highest throughput was the largest, 500-6000 bytes.

[14] Data quality and throughput values based on a channel profile of approximately 88% error-free activity, 10% cluster-error activity, and 2% burst-error activity
[15] Data quality and throughput values based on a channel profile of approximately 95% error-free activity, 4% cluster-error activity, and 1% burst-error activity
[16] Data quality and throughput values based on a channel profile of approximately 95% error-free activity, 4% cluster-error activity, and 1% burst-error activity

In the analysis of data quality performance, both the simulation and flight test results suggested that transfer frame length is not a factor in determining data quality. When the Edwards AFB channel is good, it is virtually error-free. When the channel is bad, the probability of error was typically so high (e.g., during a cluster error the probability of a bit error was approximately 0.5) that even the smallest transfer frames will probably not make it through. In addition, the actual data is packed into the source packets. So whether a transfer frame survives or not is not as important as whether the source packet, which may be divided among numerous transfer frames, makes it to the ground. Given this channel behavior, it was not surprising that transfer frame length did not play a big role in determining data quality.

Source packet length, however, did play a significant role in determining data quality. It was expected, given the channel BER, that smaller source packets would yield the best data quality. Since even a single byte error in a source packet could result in the entire source packet being deemed "bad", a long source packet being lost would result in a large amount of data also being lost. Smaller source packets on the other hand, would allow less data to be lost during a short error burst or cluster. The flight test results confirmed this prediction. A source packet length of 194 bytes yielded the best data quality. As the size of the source packet was decreased below 194 bytes, problems with the computer equipment being able to generate and process the large number of source packets necessary to maintain the channel data rate came into play and actually began to decrease data quality. The 88-10-2 and 95-4-1 simulation results found that a wider range of source packet payload lengths could produce high data quality, 500-2000 bytes and 500-6000 bytes, respectively. Considering that the maximum source packet length is

65,542 bytes, these ranges are still on the low end of possible source packet lengths. The differences between the flight test and simulation results are most likely due to real-world factors not explicitly incorporated into the simulation models, such as aircraft flight path relative to the ground station.

There was some discrepancy between the simulation and flight test results with regards to the use of Reed-Solomon to improve data quality. The simulations identified a very slight (less than 2%) advantage to using Reed-Solomon whereas the flight tests did not (data quality fell up to 4.4% using Reed-Solomon). The main reason for this difference may be that the data collected during flight testing with Reed-Solomon ON was extremely limited. As described in previous chapters, the software used to implement CCSDS during the flight test limited transfer frame payload length to a single length of 939 bytes when Reed-Solomon was ON. Although results showed that transfer frame length was not a significant factor in determining data quality, it limited the amount of data collected with Reed-Solomon ON compared to that collected with Reed-Solomon OFF. Regardless, even in the simulator, the advantages gained using Reed-Solomon were small, suggesting that the possible data quality improvements using Reed-Solomon may not be worth the effort to configure software and equipment to implement CCSDS with Reed-Solomon encoding, particularly since both simulation and flight test results suggested that Reed-Solomon significantly degrades throughput (up to 12% in the simulation results).

The CCSDS configurations yielding the best compromise between throughput and data quality were derived directly from the individual throughput and data quality results described above. In general, both the simulation and flight test results suggested that the

CCSDS configuration that maximized throughput also provided the best tradeoff between throughput and data quality. This analysis is described in depth in Chapters IV and VI.

Finally a comparison of the ATM and CCSDS protocols was performed as a precursor to future work towards using the ATM protocol in the test range community in conjunction with, or instead of, the CCSDS protocol. Overall, the performance of the ATM protocol was sufficiently close to that of CCSDS to warrant further investigation. Both the simulation and flight test results yielded similar results. Averaging the three sets of results, throughput attained using the ATM-version was 6.74% lower than that with CCSDS and data quality was 0.51% lower. While the throughput performance of the ATM protocol was lower than that of CCSDS in this study, the results were "close enough" that with further "tuning" the ATM protocol may be able to offer comparable throughput performance.

7.2 Recommendations

This research has mapped the relationships between the primary CCSDS parameters (transfer frame length, source packet length, and Reed-Solomon encoding) and the resulting protocol performance (measured in terms of throughput and data quality). It has also provided guidance with regards to optimizing use of the protocol to meet mission-specific requirements. The results of this research should suffice for meeting the basic needs of the test community for configuring equipment for telemetry data transmission. Further investigation of using the ATM protocol in the test range environment is highly recommended, alone or in conjunction with the CCSDS protocol. To facilitate that work it would be beneficial to enhance the OPNET simulation model to explicitly include the effects of dynamic environmental variables. While the difference those real-world variables made to this research effort was relatively minor, an in-depth investigation of an ATM-CCSDS-hybrid-protocol would benefit from a more robust model of channel behavior.

The CCSDS packet telemetry protocol clearly merits use in the DoD test range community. With further optimization, and possible fusion with the ATM protocol, it may prove to be the key to meeting DoD telemetry system requirements at test ranges around the country.

APPENDIX A - OPNET Model Design

A.1 OPNET Model

OPNET is a modeling and simulation tool that provides an environment for analysis of communication networks. It defines a model using a three-layer hierarchical structure. The highest layer, referred to as the network layer, is where the network topology is defined. In the second layer, called the node layer, the internal structure and behavior of each node in the network model is defined. Finally, the process layer specifies logic or control flow among components in the form of a finite state machine.

The N-source network topology used for the design and development of the packet telemetry system model is shown in Figure 35. Source and destination end-systems are connected to a pair of switches that communicate via a point-to-point link. The figure also shows node models for the airborne and ground switches, as well as the on-board data sources. The node architecture for the on-board data sources consists of N data sources modeled as one "large" data source. The underlying process model is responsible for producing source packets and organizing them into data segments for subsequent insertion into a transfer frame. The node architecture for the airborne switch (Switch 1) consists of a single processor responsible for completing the construction of transfer frames, including insertion of transfer frame idle data if necessary, and managing the transmission of transfer frames off the aircraft in such a way as to maintain the 1 Mbps channel data rate. The node architecture for the ground switch (Switch 2) consists of a single point-to-point receiver to capture the incoming transfer frames and a processor to reconstruct the source packets.

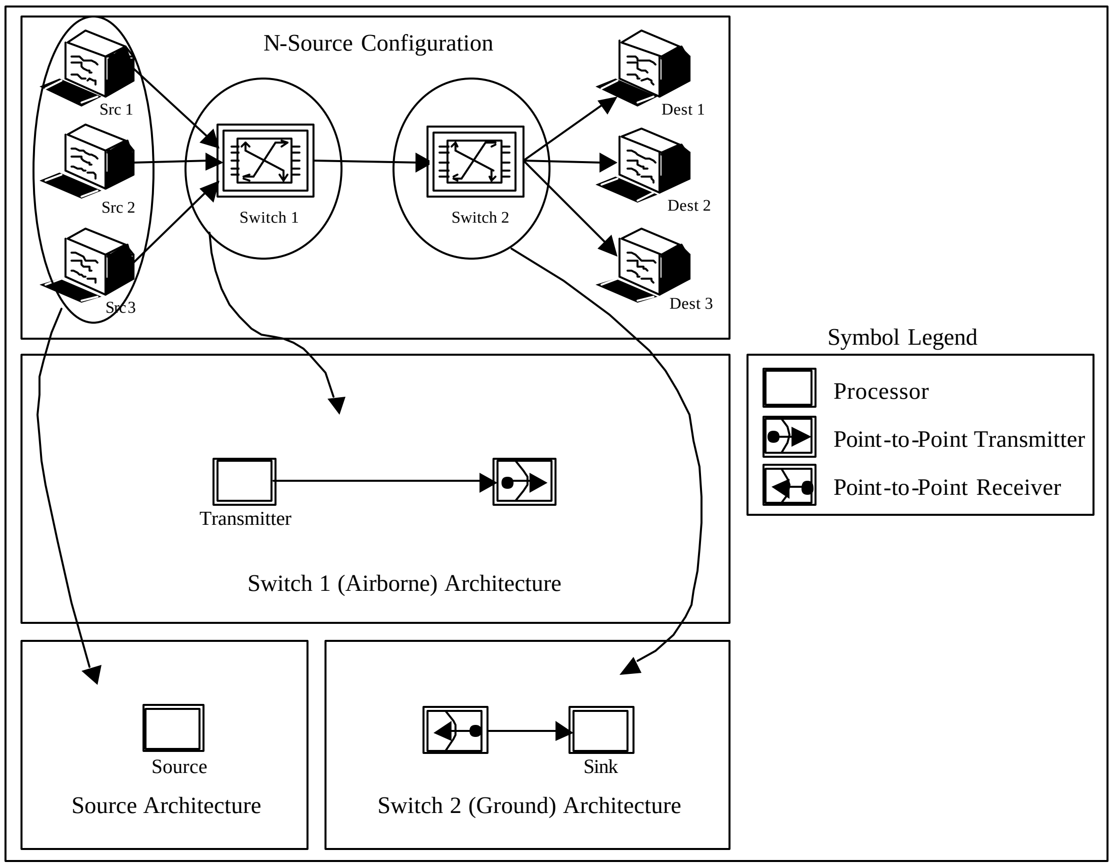


Figure 35. The OPNET Model

The packet telemetry system is modeled in OPNET using a point-to-point wired connection rather than a wireless model. Although OPNET is capable of modeling a wireless environment, doing so adds unnecessary complexity to the model/simulation. For example, the transfer of telemetry data involves only one source node (the aircraft) and one destination node (the ground station). A typical wireless network, on the other hand, consists of multiple sources and multiple receivers, where each receiver can potentially receive every packet that is broadcast. In addition, terrain, elevation, and antenna placement effects on radio propagation and signal attenuation are accounted for in the channel link model, making the use of OPNET's terrain modeling module (part of the wireless model) superfluous. For these reasons, OPNET's wireless model is not used.

Source packets are produced by on-board data sources. These source packets are segmented into transfer frames and transmitted over the physical medium. The segmentation of source packets and subsequent transmission of transfer frames are represented by the Source and Transmitter process models, respectively. The OPNET process modeling methodology [16] was used in the development of the Source and Transmitter process models. The key steps in this modeling methodology include: definition of system context, process level decomposition, enumeration of events (per process), state-level decomposition (per process), construction of an event response table (per process), and construction of the finite state machine (per process). This development of the OPNET Source and Transmitter process models is described in Appendix B.

A.2 Segmentation and Reassembly Buffer

The process of organizing source packets into transfer frames on the aircraft and later reassembling the source packets from the transfer frames received on the ground was done using two specialized buffers. The first, a segmentation buffer, was used in the airborne portion of the model. Each newly created source packet was put into one end of the segmentation buffer. Segments of a designated length could then be pulled out the other end of the buffer in a first-in-first-out manner. The length of the segment pulled out was equal to the length of the data field of the transfer frame being tested. Segments were padded to the requested size with transfer frame idle data if necessary. Transfer frame header and synchronization bytes were then added to the data segment and the completed transfer frame sent through the channel. On the receiving end, a reassembly buffer was used. As transfer frames arrived on the ground, the header and synchronization bytes were stripped away and the remaining data segment put into the reassembly buffer. A specialized OPNET Kernel Procedure was then used to reassemble the data in the reassembly buffer back into the original source packets. Completely reassembled source packets were removed from the buffer when available and statistical information recorded (e.g., end-to-end delay) for use in the final CCSDS analysis. To maintain the 1 Mbps channel data rate, "idle" transfer frames were created and sent through the channel if the segmentation buffer was empty at the time a transfer frame was needed. These idle transfer frames were identified using an arbitrary "0001" synchronization pattern. Once received on the ground, idle transfer frames were identified and destroyed instead of being placed in the reassembly buffer.

A.3 Channel Characterization

To emulate the bursty-error behavior of the downlink channel, a custom-designed link model was used to connect Switch 1 and Switch 2. Numerous efforts have been made to measure bit error performance of aeronautical telemetry links. Picking one channel characterization is highly problematic since there is no single air-to-ground channel scenario. Flight profile, weather, vehicle speed ranges, antenna type and placement, and local terrain are all uncontrolled variables that significantly influence channel characteristics.

Despite these difficulties, flight tests conducted by the ARTM project office have confirmed the two primary sources of bit errors and short-term link failures in the traditional test corridors[17] at Edwards AFB are "error bursts" and "error clusters". An error burst is a sporadic, impulse-type event, where the bit error probability (BEP) suddenly degrades to the range of 10^{-3} to 10^{-5}. The duration of error bursts (at T-39 speeds over the baseline corridors) is in the range of a few hundred milliseconds (msec) to one second. The second type of error, an error cluster, occurs more frequently and is associated with strong, two-ray, frequency selective fades. They are primarily seen when the receiving antenna main lobe grazes the ground or horizon. BEP values during an error cluster are approximately 0.5. In reality, the receiver/detector has lost synchronization--the link is broken. The link model used in the OPNET design was built to emulate the real-world channel behavior as closely as possible. This is further described in the next section.

A.4 Three-State Channel Model

Errors on digital telemetry transmission systems are known to be bursty in nature. Hence, models that treat the channel as being memoryless do not adequately represent its error performance. In this study, a three-state Markov chain is used to model the bursty-error characteristics of the channel [21]. This type of model was first proposed by Gilbert. According to the original two-state Gilbert model, at any instant in time the channel is assumed to be in either one of two states. This is shown in Figure 36. In the

[17] The ARTM project used four of the traditional test corridors at Edwards AFB, however the most useful (repeatable) baseline link performance data was obtained from three--"Cords Road", "Black Mountain", and one of the high altitude supersonic corridors.

good state, *G*, the probability of error is so small, 10^{-12}, that it is assumed to be zero. In the bad state, *B*, errors occur with probability 1 - *h* where *h* is the probability of no bit error. The duration of each state is expressed in terms of transition probabilities. A transition from *G* to *B* occurs with probability *P* and a transition from *B* to *G* with probability *p*. The model remains in state *G* with probability *Q* = 1 - *P*, and remains in state *B* with probability *q* = 1 - *p*.

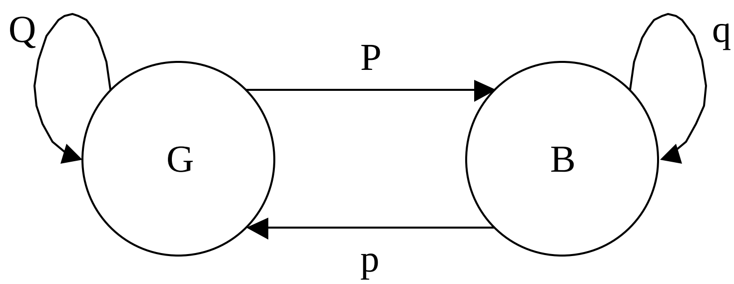


Figure 36. The Original Two-State Gilbert Model

From ARTM's work to characterize the telemetry link it is known that two types of errors can occur - error clusters and error bursts. Although it is difficult to precisely quantify the channel behavior, for the purposes of this research only an approximate level of accuracy is required. Table 14 summarizes the channel profile that was used. These values are based on "typical" results from ARTM flight tests.

Table 14. Channel Profile

State	Percentage of time spent in state (%)	BEP	Duration (msec)
Error-free	88	0	variable
Error-cluster	10	0.5	100-1000
Error-burst	2	10^{-5} - 10^{-3}	200

To reflect the distinctive behavior of the two types of error activity, the two-state Gilbert model is expanded to a three-state variation. This is shown in Figure 37. In this model, P_c and P_b are the probabilities of transitioning from the good state, G, to the bad states $B_{cluster}$ and B_{burst}, respectively. Q, q_c, and q_b are the probabilities of staying in G, $B_{cluster}$, and B_{burst}, while p_c and p_b are the probabilities of transitioning from the $B_{cluster}$ and B_{burst} states back to G.

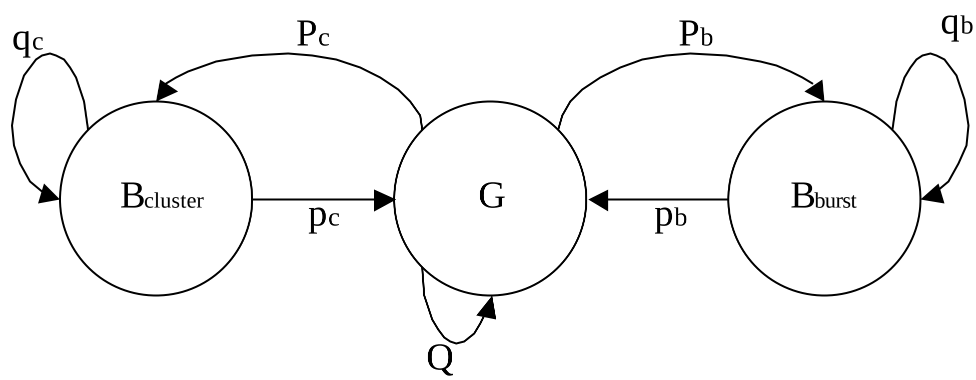


Figure 37. Three-State Channel Model

The probability of a state transition in the three-state model is evaluated based on elapsed time. The time spent in each of the three states is modeled as an exponentially distributed random variable with different means. This time modulated approach significantly reduces the computational burden inherent in schemes that evaluate state transitions on a bit-by-bit basis.

To reflect the channel profile (Table 14) as closely as possible, the byte error probabilities and mean duration times shown in Table 15 were chosen for the OPNET link model used to connect Switch 1 and Switch 2. In the error-burst state, the bit-error probability is randomly chosen each time the state is entered from the three values shown. These values correspond to 10^{-3}, 10^{-4}, and 10^{-5} respectively. In the error-cluster state, the mean duration is chosen randomly each time the state is entered from the values shown. These values were chosen to emulate the 100-1000 msec range in the ARTM data and at the same time achieve the 88, 10, 2% breakdown of time spent in each state. Similarly, the mean duration in the error-free state is chosen randomly from the values shown in the table. These times were derived from a sample bit-error mask provided by the ARTM office. The repetition of some values is done to increase their probabilistic weighting during the random selection. This is done to mirror the frequency of occurrence of these times in the provided sample error mask, while at the same time achieve the 88, 10, 2% breakdown of time spent in each state.

Table 15. Channel Model Values Used in OPNET Model

State	Byte Error Probabilities[18]	Mean Time in State (sec)
Error-free (G)	0	26, 3.3, 3.3, 0.6, 0.6, 0.6, 0.6, 0.08, 0.08, 0.05, 0.05
Error-cluster ($B_{cluster}$)	0.9961	1.0, 0.4, 0.1
Error-burst (B_{burst})	0.007972055, 0.00079972, 0.000079997	0.2

A.5 Conversion From Bits to Bytes

The CCSDS packet telemetry protocol uses an optional 16 Reed-Solomon byte error correction capability. This encoding scheme can correct up to 16 Reed-Solomon byte errors in each codeword, where one codeword is 223 bytes in length. Translating this into OPNET terminology, when Reed-Solomon encoding is used, the error correction

[18] The values in this column represent Byte Error Probabilities derived from the Bit Error Probabilities provided by ARTM.

threshold is 16 bytes for every block of 223 transmitted bytes. When a codeword is received, the number of byte-errors in that codeword is calculated. If more than 16 byte-errors have occurred, the codeword is marked as "bad". Otherwise the codeword is accepted as being "good". The CCSDS protocol transmits data in transfer frames, rather than codewords. Once received on the ground, each transfer frame is decoded and analyzed for errors one codeword at a time. To simplify error-correction calculations in the OPNET model used in this research, the number of byte-errors is calculated for the entire received transfer frame, rather than breaking it into 223-byte codewords, and this number compared to the corresponding multiple of 16 to determine if the transfer frame is accepted as "good" or "bad". With a byte-error probability of 0.9961, cluster errors are virtually equivalent to a total link failure. During these times, byte errors are so overwhelming that no codewords, and hence no transfer frames, will get through under the error threshold. Since cluster errors make up 83.33% of all error behavior, simplifying the error calculations to the transfer frame level simplifies the model and should not greatly affect the total number of "good" and "bad" transfer frames.

Typically, the OPNET software operates on data at the bit-level. From the above discussion on the correction of byte errors using Reed-Solomon, however, manipulating the model data at the byte-level was the more straightforward approach. A paradigm shift was in order. To start, the channel data rate was divided by eight to represent *bytes*-per-second (Bps), rather than *bits*-per-second (bps). Each "OPNET bit" could then be viewed as one byte. The existing C++ code could then be used without any further manipulation other than making sure numerical values are stated in units of bytes rather than bits.

The bit error probability values provided by the ARTM office were converted to byte error probabilities. Making the simplifying assumption that during a period of error activity, whether it is an error cluster or error burst, the bit errors are independent and uniformly distributed, the values could be converted using basic probabilistic methods. This is shown below.

> Let p_{err} = the probability that a bit is in error
>
> Then, the probability a bit is not in error is $\mathbf{1 - p_{err}}$
>
> The probability that eight bits in a row are all good is $\mathbf{(1 - p_{err})^8}$
> (this equals the probability of a byte being received error free)
>
> Thus the probability of a single byte being in error is $\mathbf{1 - (1 - p_{err})^8}$
>
> So, the byte-error-probability is $\mathbf{1 - (1 - p_{err})^8}$**, where** $\mathbf{p_{err} = BEP}$

The byte-error probability values shown in Table 15 were calculated in this manner. Again, since cluster errors make up 83.33% of all error behavior and during a cluster error almost no bits make it through unscathed, making the assumption that bit errors are independent and uniformly distributed simplifies the model and should not greatly affect the total number of "good" and "bad" transfer frames received.

A.6 Synchronization Pattern

Attached to the beginning of each transfer frame is a 32-bit frame synchronization marker used by the receiving network to acquire synchronization with the frame boundaries after transmission through the data channel. These sync bits are removed before the Reed-Solomon encoding process. In the OPNET model, however, they are not removed and counted against the 16-byte error threshold if any bytes in the sync pattern come through the channel in error. This simplifying assumption was made for three reasons. The first reason for this is that 83.33% of the error behavior is due to a cluster error during which virtually no transfer frames make it through the channel under the error threshold. Whether the sync bits are included in the error calculations or not, the transfer frame is still very unlikely to be accepted as "good". Second, the sync bits make up only a small percentage of the total bits transmitted (as little as 0.36%, and as much as 21%). Although it is equally probable an error could occur in any one sync bit, the likelihood of errors occurring in the synchronization portion of the transmitted block versus the data portion of the transmitted block is lower in most cases. Finally, the 32-bit synchronization pattern was selected because it provides very good synchronization qualities in a noisy channel environment [6]. Synchronization is customarily confirmed at the receiving end by making further checks and when the frame is of fixed length, as it is in the case of CCSDS, conventional "flywheeling" techniques can be used to maintain frame synchronization in a noisy environment [6]. Thus, some of the sync bits can be lost to error and synchronization will still be possible.

A.7 Fixed Propagation Delay

In reality, the airborne transmitter's distance from the ground receiver is changing throughout the telemetry downlink due to altitude and position changes of the aircraft. Additionally, the altitude/position profile of one flight could vary greatly from that of another flight. Modeling every case would be as equally difficult as choosing one typical case. Comparing the effects of distance on transfer frame and source packet length is beyond the scope of this thesis and is left for future study. A fixed propagation delay of

1.75e-05 seconds was used. This value was based on a traveling distance of 3500 meters and traveling speed of ? *c*, where *c* is the speed of light. By fixing the propagation delay, the effects of jitter in the received data stream are not visible in the simulation data. In reality, these disturbances in the otherwise constant data stream are most likely slight and easily overcome by the synchronization software. During cluster and burst errors, the effects of jitter are all but "lost in the weeds".

B.1 OPNET Top-Level and Node Models

The top level of the OPNET model is shown in Figure 38. The Airborne and Ground nodes are shown in Figure 39 and Figure 40, respectively. The remainder of the appendix breaks down the design of each process model contained in these two nodes.

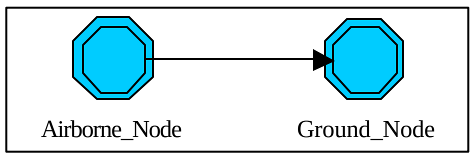


Figure 38. Top Level View of OPNET Telemetry Model

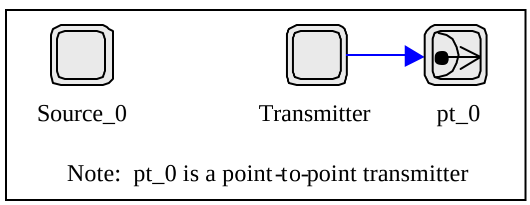


Figure 39. Airborne_Node Node Model

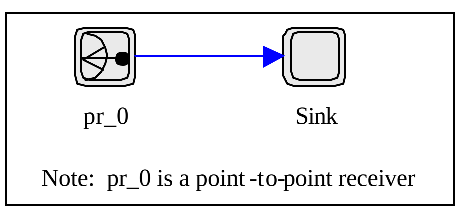


Figure 40. Ground_Node Node Model

B.2 Process Model Development

B.2.1 Source Process Model Development

Logical events that can occur at the Source include 'start source packet generation, 'stop packet generation', 'packet generate', and 'packet generation disabled'. Table 16 enumerates the events that can occur at the Source and the associated interrupt types.

Table 16. Source Events

EVENT	EVENT DESCRIPTION	INTERRUPT TYPE
START	Indicates a start time for packet generation activities	Self
STOP	Indicates a stop time for packet generation activities	Self
DISABLED	Packet source has been disabled	Self
PACKET GENERATE	It is time to generate the next source packet	Self

Table 17 shows the state-level decomposition of the Source process.

Table 17. State-Level Decomposition of Source Process

STATE NAME	STATE DESCRIPTION
Init	Initial State. Segmentation and Reassembly buffer is initialized. Initialize start/stop times, statistic handles, and other miscellaneous variables
Generate	Schedule PACKET_GENERATE interrupt based on source packet interarrival rate
MakeSP	Construct a source packet
Segment	Insert source packet into Segmentation and Reassembly buffer
Stop	Cancel generation of the next source packet and go into a silent mode

Table 18 outlines the actions taken when an event occurs within the Source process. Each row of this table represents a combination of a state and an event and their associated conditions. The different actions performed for each combination and the resulting next state are listed. Figure 41 shows the state machine implementation for the Source process model.

Table 18. Source Event Response Table

CURRENT STATE	LOGICAL EVENT	CONDITION	ACTION	NEXT STATE
Init	START	none	Record type of interrupt that occurred	Generate
	DISABLED	none	Record type of interrupt that occurred	Stop
Generate	PACKET GENERATE	none	Record type of interrupt that occurred	MakeSP
	STOP	none	Record type of interrupt that occurred	Stop

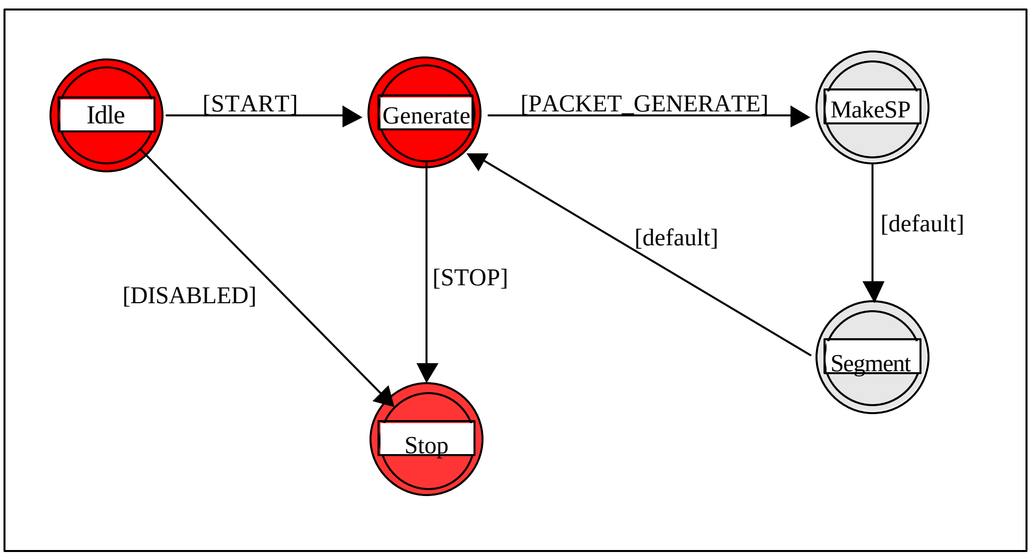


Figure 41. Source State Machine Implementation

B.2.2 Transmitter Process Model Development

Logical events that can occur at the Transmitter include 'start operations' and 'send frame'. Table 19 enumerates the events that can occur at the Transmitter and the associated interrupt types.

Table 19. Transmitter Events

EVENT	EVENT DESCRIPTION	INTERRUPT TYPE
START_OP	The Segmentation and Reassembly buffer has been initialized (by Source node). Begin accessing buffer	Remote
SEND FRAME	It is time to send the next transfer frame	Self

Table 20 shows the state-level decomposition of the Transmitter process.

Table 20. State-Level Decomposition of Transmitter Process

STATE NAME	STATE DESCRIPTION
Initial	Initial State. Calculate delay interval between transfer frame transmissions
Manager	Access Segmentation and Reassembly buffer. If a data segment is available in the buffer, remove it and construct a transfer frame. If no data is available from the buffer, create an 'idle' transfer frame
Send TF	Send completed transfer frame (actual or idle) to the point-to-point transmitter for transmission off the aircraft

Table 21 outlines the actions taken when an events occurs within the Transmitter process. Each row of this table represents a combination of a state and an event and their associated conditions. The different actions performed for each combination and the resulting next state are listed. Figure 42 shows the state machine implementation for the Transmitter process model.

Table 21. Transmitter Event Response Table

CURRENT STATE	LOGICAL EVENT	CONDITION	ACTION	NEXT STATE
Initial	START_OP	none	Record type of interrupt that occurred	Manager
Send TF	SEND_FRAME	none	Record type of interrupt that occurred	Manager

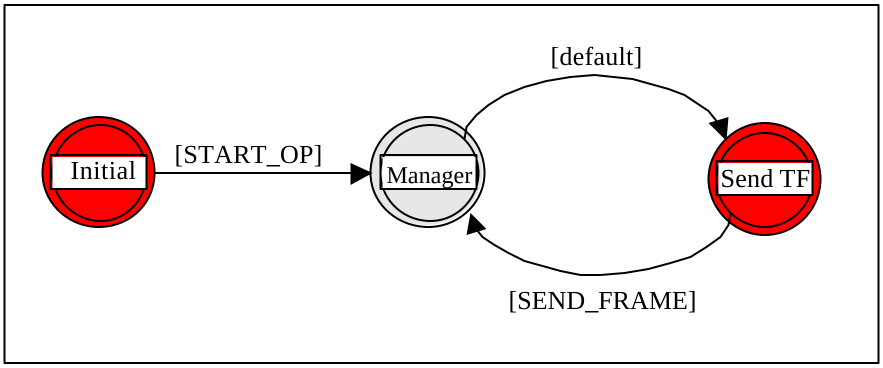


Figure 42. Transmitter State Machine Implementation

B.2.3 Sink Process Model Development

Logical events that can occur at the Sink include 'gnd arrival' and 'end simulation'. Table 22 enumerates the events that can occur at the Sink and the associated interrupt types.

Table 22. Sink Events

EVENT	EVENT DESCRIPTION	INTERRUPT TYPE
GND_ARRIVAL	The next transfer frame has arrived	Stream
END_SIMULATION	Simulation time has expired. Time to calculate final statistics	Self

Table 23 shows the state-level decomposition of the Sink process.

Table 23. State-Level Decomposition of Sink Process

STATE NAME	STATE DESCRIPTION
Init	Initial State. Create Reassembly buffer. Initialize variables
Process	Determine if arriving transfer frame is good/bad. If bad, discard and collect statistical data. If good, unpack source packet segment and place into Reassembly buffer. Check for complete source packets in Reassembly buffer. If complete source packet available, remove, collect statistical data, then discard source packet
ENDSIM	Using statistical data collected throughout simulation, calculate desired performance metrics (throughput and data quality). Output information to out_file

Table 24 outlines the actions taken when an events occurs within the Sink process. Each row of this table represents a combination of a state and an event and their associated conditions. The different actions performed for each combination and the resulting next state are listed. Figure 43 shows the state machine implementation for the Sink process model.

Table 24. Sink Event Response Table

CURRENT STATE	LOGICAL EVENT	CONDITION	ACTION	NEXT STATE
Process	GND_ARRIVAL	none	Record type of interrupt that occurred	Process
	END_SIMULATION	none	Record type of interrupt that occurred	ENDSIM
ENDSIM	none	none	Record type of interrupt that occurred	none

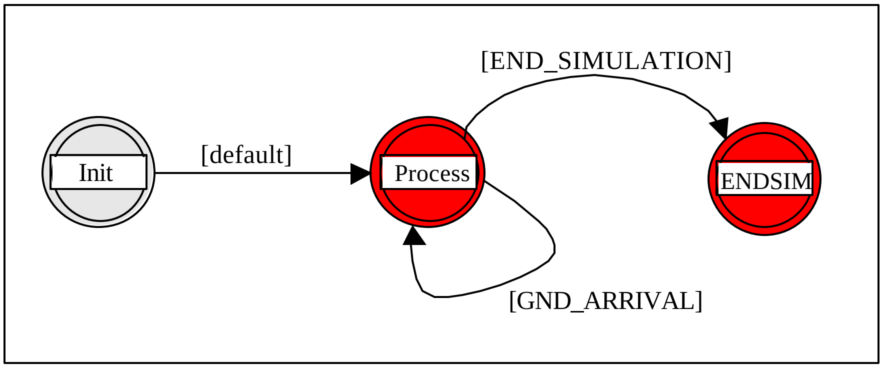


Figure 43. Sink State Machine Implementation

APPENDIX C - Simulation Length Calculation

Rather than show the simulation length calculations for all test cases, they will be shown here for one case. Calculations for the other cases follow the same procedure.

Simulation Length Calculation:

Configuration: Run = 12
Transfer Frame Payload Length = 200 Bytes
Source Packet Payload Length = 60000 Bytes
Source Packet Generation Rate = 117,920 Bps

First, the throughput of each individual source packet was recorded during a two-minute preliminary run. The sample mean of the source packet throughput was 2986.0223 Bps, and the sample standard deviation was 18,509.8466. To get the throughput accurate to within 10% (roughly ±18,000 Bps) at 80% confidence, 6316 source packets had to be observed (processed through the system). This number was calculated as follows:

The number of observations, *n*, required to achieve ±*r*% accuracy at an 80% confidence level is [12]:

$$n = \left(\frac{100zs}{r\bar{x}} \right)^2$$

where, $\bar{x}$ = sample mean
s = sample standard deviation
r = desired accuracy
z = normal variate of the desired confidence level

Here, $\bar{x}$ = 2986.0233, s = 18509.8466, r = 10, z = 1.282

Substituting, $n = \left(\frac{100(1.282)(18509.8466)}{(10)(2986.0233)} \right)^2 = 6315.32$

A total of 6316 observations are needed.

From this, simulation length was determined to be 3300 seconds. This was calculated based on the time to transmit and receive 6316 source packets. This is shown below:

$$6316 \text{ source packets} \times \frac{60{,}006 \text{ bytes}}{\text{source packet}} \times \frac{1}{117920 \text{ bytes}/\text{sec}} = 3214.03 \text{ seconds}$$

To accommodate other data points with similar length requirements, simulation length was set at 3300 seconds.

APPENDIX D - ATM Equivalent Calculation

Given the individual header/overhead requirements of the ATM and CCSDS protocols, it was not possible to configure a CCSDS transfer frame, and/or source packet, to have 48 bytes of useful data and five bytes of overhead as exists in an ATM cell. With this "simple" solution not available, the next best solution was to conduct the ATM/CCSDS performance comparison using a CCSDS transfer frame-source packet combination of the same data-to-overhead ratio as an ATM cell, namely 48:5. The result was a transfer frame payload length of 179 bytes and a source packet payload length of 173 bytes. The calculations used to arrive at this result are given below.

We want the data-to-overhead ratio of the solution to be 48:5. Another way to look at it is we want the fraction of overhead in the solution to be 5/53.

Let x = the number of bytes of useful data in the embedded source packet
Overhead due to the transfer frame header = 8 bytes (Reed-Solomon turned OFF)
Overhead due to the source packet header = 6 bytes
Overhead due to the synchronization bytes = 4 bytes

The resulting equation is,

$$\frac{8+6+4}{8+6+4+x} = \frac{5}{53}$$

$$\text{Solving,} \quad x = 172.8$$

Therefore, the source packet payload length was set at 173 bytes.

The resulting transfer frame payload length was 173 bytes plus the six source packet header bytes, or 179 bytes.

APPENDIX E – Confidence and Accuracy Calculations

The configuration of parameters that had the largest variance in throughput and data quality results was used to calculate the reported confidence and accuracies. This was done for both sets of simulations, as well as the flight test.

The number of replications, *n*, required to achieve ±*r*% accuracy at a particular confidence level is [12]:

$$n = \left(\frac{100zs}{r\overline{x}} \right)^2$$

where, $\overline{x}$ = sample mean
s = sample standard deviation
r = desired accuracy
z = normal variate of the desired confidence level

Given the number of replications, sample mean, and sample standard deviation, several confidence levels were inserted (e.g., 80%, 90%, 95%, 98%) and the resulting accuracies calculated. The highest confidence level producing satisfactory accuracy levels for both throughput and data quality was then reported. The confidence/accuracy calculations are given below.

<u>88-10-2 Simulation Model</u>:
CCSDS configuration = (TF = 400 bytes; SP = 1400 bytes; RS = OFF)
Throughput:
Given: n = 5; $\overline{x}$ = 106,672.00 Bps; s = 245.60; z = 1.645
Solving, r = 0.1694
Then, 0.1694 × 106,672.00 = 180 $\rightarrow$ So, throughput accurate to within ±180 Bps

Data quality:

Given: n = 5; $\bar{x}$ = 88.04%; s = 0.2027; z = 1.645

Solving, r = 0.1694

Then, 0.1694 × 88.04 = 0.15

→ So, data quality accurate to within ±0.15 percentage points

<u>95-4-1 Simulation Model</u>:

CCSDS configuration = (TF = 600 bytes; SP = 60,000 bytes; RS = OFF)

Throughput:

Given: n = 5; $\bar{x}$ = 111,035.74 Bps; s = 172.30; z = 1.645

Solving, r = 0.1142

Then, 0.1142 × 111,035.74 = 127 → So, throughput accurate to within ±127 Bps

Data quality:

Given: n = 5; $\bar{x}$ = 90.67%; s = 0.1400; z = 1.645

Solving, r = 0.1136

Then, 0.1136 × 90.67 = 0.103

→ So, data quality accurate to within ±0.103 percentage points

<u>Flight Test</u>:

CCSDS configuration = (TF = 400 bytes; SP = 2000 bytes; RS = OFF)

Throughput:

Given: n = 4; $\bar{x}$ = 112,662.87 Bps; s = 1457.64; z = 1.282

Solving, r = 0.8290

Then, 0.8290 × 112,662.87 = 934 → So, throughput accurate to within ±934 Bps

Data quality:

Given: n = 4; $\bar{x}$ = 95.08%; s = 1.444; z = 1.282

Solving, r = 0.9735

Then, 0.9735 × 95.08 = 0.92

→ So, data quality accurate to within ±0.92 percentage points

<u>Flight Test ATM Data</u>:

Throughput:

Given: n = 4; $\bar{x}$ = 107,898.93 Bps; s = 2128.77; z = 1.282

Solving, r = 1.788

Then, 1.788 × 107,898.93 = 1929 → So, throughput accurate to within ±1929 Bps

Data quality:

Given: n = 4; $\bar{x}$ = 96.87%; s = 1.730; z = 1.282

Solving, r = 1.619

Then, 1.619 × 96.87 = 1.57

→ So, data quality accurate to within ±1.57 percentage points

88-10-2 Simulation

Throughput:

Source	Sum of Squares	% Contribution	Degrees of Freedom	Mean Square	F Value	Prob > F
Model	5.759E+011		167	3.448E+009	6.664E+005	< 0.0001
TF	2.094E+011	36.4	5	4.188E+010	8.092E+006	< 0.0001
SP	1.199E+011	20.8	13	9.227E+009	1.783E+006	< 0.0001
RS	1.783E+011	31.0	1	1.783E+011	3.446E+007	< 0.0001
TF-SP	4.531E+009	0.79	65	6.971E+007	13471.97	< 0.0001
TF-RS	5.889E+010	10.2	5	1.178E+010	2.276E+006	< 0.0001
SP-RS	3.594E+009	0.62	13	2.764E+008	53419.75	< 0.0001
TF-SP-RS	1.227E+009	0.21	65	1.888E+007	3648.64	< 0.0001
Pure Error	3.477E+006	0.00060	672	5174.79		
Cor Total	5.759E+011		839			

- Where, TF = transfer frame payload length; SP = source packet payload length; RS = Reed-Solomon encoding
- The Model F-value of 666397.83 implies there is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case, TF, SP, RS, TF-SP, TF-RS, SP-RS, and TF-SP-RS are significant model terms.

Data Quality:

Source	Sum of Squares	% Contribution	Degrees of Freedom	Mean Square	F Value	Prob > F
Model	1.219E+005		167	729.72	1.981E+005	< 0.0001
TF	18.28	0.015	5	3.66	992.37	< 0.0001
SP	1.211E+005	99.3	13	9314.77	2.528E+006	< 0.0001
RS	181.69	0.15	1	181.69	49316.89	< 0.0001
TF-SP	311.86	0.26	65	4.80	1302.29	< 0.0001
TF-RS	86.22	0.07	5	17.24	4680.68	< 0.0001
SP-RS	57.21	0.05	13	4.40	1194.45	< 0.0001
TF-SP-RS	116.51	0.10	65	1.79	486.52	< 0.0001
Pure Error	2.48	0.002	672	3.684E-003		
Cor Total	1.219E+005		839			

- Where, TF = transfer frame payload length; SP = source packet payload length; RS = Reed-Solomon encoding
- The Model F-value of 198071.57 implies there is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case, TF, SP, RS, TF-SP, TF-RS, SP-RS, and TF-SP-RS are significant model terms.

Flight Test

Throughput:

Source	Sum of Squares	% Contribution	Degrees of Freedom	Mean Square	F Value	Prob > F
Model	5.982E+009		40	1.496E+008	20.46	0.1738
TF	2.472E+009	41.3	5	4.946E+008	67.69	0.0920
SP	2.156E+009	36.0	5	4.311E+008	59.00	0.0985
RS	7.322E+008	12.2	1	7.322E+008	100.19	0.0634
TF-SP	4.403E+008	7.4	25	1.761E+007	2.41	0.4747
TF-RS	0.000	0.0	0			
SP-RS	3.452E+007	0.58	5	6.904E+006	0.94	0.6493
TF-SP-RS	0.000	0.0	0			
Pure Error	7.308E+006	0.12	1	7.308E+006		
Cor Total	5.989E+009		41			

- Where, TF = transfer frame payload length; SP = source packet payload length; RS = Reed-Solomon encoding
- The Model F-value of 20.46 implies there is a 17.38% chance that a "Model F-Value" this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case there are no significant model terms.

Data Quality:

Source	Sum of Squares	% Contribution	Degrees of Freedom	Mean Square	F Value	Prob > F
Model	1185.14		40	29.63	103.06	0.0780
TF	81.12	6.8	5	16.22	56.43	0.1007
SP	771.17	65.1	5	154.23	536.51	0.0328
RS	0.25	0.02	1	0.25	0.87	0.5222
TF-SP	285.11	24.1	25	11.40	39.67	0.1249
TF-RS	0.00	0.0	0			
SP-RS	19.94	1.7	5	3.99	13.87	0.2009
TF-SP-RS	0.00	0.0	0			
Pure Error	0.29	0.02	1	0.29		
Cor Total	1185.43		41			

- Where, TF = transfer frame payload length; SP = source packet payload length; RS = Reed-Solomon encoding
- The Model F-value of 103.06 implies there is a 7.80% chance that a "Model F-Value" this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case, SP is a significant model term.

APPENDIX G - Raw Simulation Data (88-10-2 Channel Model)

This appendix lists the throughput, data quality, and channel utilization results from each simulation run using the 88-10-2 channel model. Values shown are the arithmetic mean of data from five samples. This sample size yielded a worst-case confidence of 90%. Throughput data is accurate to within ±180 Bps. Data quality data is accurate to within ±0.15 percentage points. Confidence and accuracy calculations are shown in Appendix E. The following tables and figures are provided in this appendix:

Table 25. Raw Experimental Results in Tabular Form (Part 1 of 5)

Type	Run	TF Len (bytes)	SP Len (bytes)	RS	SP Data Rate (Bps)	Sim Length (sec)	Throughput (Bps)	SP Data Quality (%)	Channel Utilization (%)
Initial	1	41	5	N	92865	35	39514.29	42.55	99.999
Initial	2	41	194	N	95910	35	84006.43	87.59	99.994
Initial	3	41	500	N	96390	35	85194.28	88.39	99.984
Initial	4	41	2000	N	96620	35	84868.57	87.88	99.941
Initial	5	41	20000	N	96690	10800	82803.70	85.64	99.998
Initial	6	41	60000	N	96700	10800	78900.00	81.60	99.994
Initial	7	200	5	N	116720	35	48070.49	41.19	99.995
Initial	8	200	194	N	116720	35	102609.38	87.91	99.995
Initial	9	200	500	N	117520	35	103762.88	88.30	99.985
Initial	10	200	2000	N	117810	35	103588.56	87.96	99.947
Initial	11	200	20000	N	117910	3300	101430.30	86.02	99.995
Initial	12	200	60000	N	117920	3300	97530.91	82.72	99.985
Initial	13	400	5	N	120720	35	49283.17	40.83	99.991
Initial	14	400	194	N	120720	35	105274.38	87.21	99.991
Initial	15	400	500	N	121040	35	106471.42	87.97	99.981
Initial	16	400	2000	N	121250	35	106422.88	87.81	99.944
Initial	17	400	20000	N	121350	3300	104556.38	86.16	99.995
Initial	18	400	60000	N	121350	3300	100290.90	82.65	99.985
Initial	19	600	5	N	122110	35	49698.43	40.70	99.986
Initial	20	600	194	N	122110	35	106076.98	86.87	99.986
Initial	21	600	500	N	122110	35	107445.70	88.00	99.986
Initial	22	600	2000	N	122440	35	107542.88	87.86	99.944
Initial	23	600	20000	N	122540	3300	105572.14	86.15	99.995
Initial	24	600	60000	N	122540	3300	101585.46	82.91	99.985
Initial	25	800	5	N	122820	35	49809.97	40.56	99.981
Initial	26	800	194	N	122820	35	106272.08	86.53	99.981
Initial	27	800	500	N	122820	35	107751.42	87.74	99.981
Initial	28	800	2000	N	123040	35	107931.44	87.73	99.944
Initial	29	800	20000	N	123140	3300	105993.94	86.08	99.995
Initial	30	800	60000	N	123150	3300	101861.80	82.72	99.985
Initial	31	1000	5	N	123250	35	49856.57	40.45	99.977
Initial	32	1000	194	N	123250	35	106389.60	86.32	99.977
Initial	33	1000	500	N	123250	35	107951.42	87.59	99.977
Initial	34	1000	2000	N	123430	35	108022.86	87.52	99.931
Initial	35	1000	20000	N	123500	750	106213.34	86.01	99.977
Initial	36	1000	60000	N	123510	750	102352.00	82.92	99.934

Table 26. Raw Experimental Results in Tabular Form (Part 2 of 5)

Type	Run	TF Len (bytes)	SP Len (bytes)	RS	SP Data Rate (Bps)	Sim Length (sec)	Throughput (Bps)	SP Data Quality (%)	Channel Utilization (%)
Initial	37	41	5	Y	24040	35	9936.00	41.33	99.995
Initial	38	41	194	Y	24240	35	21179.26	87.38	99.976
Initial	39	41	500	Y	24270	35	21528.57	88.75	99.937
Initial	40	41	2000	Y	24285	35	21542.86	88.92	99.764
Initial	41	41	20000	Y	24288	10800	20383.33	83.93	99.992
Initial	42	41	60000	Y	24288	10800	18411.11	75.82	99.977
Initial	43	200	5	Y	67170	35	27633.14	41.14	99.992
Initial	44	200	194	Y	67170	35	58970.46	87.80	99.992
Initial	45	200	500	Y	67432	35	60000.00	88.98	99.975
Initial	46	200	2000	Y	67530	35	60342.86	89.42	99.907
Initial	47	200	20000	Y	67565	3300	59127.27	87.51	99.991
Initial	48	200	60000	Y	67565	3300	56327.27	83.37	99.973
Initial	49	400	5	Y	87380	35	35869.71	41.05	99.987
Initial	50	400	194	Y	87380	35	76546.86	87.60	99.987
Initial	51	400	500	Y	87550	35	77928.57	89.02	99.974
Initial	52	400	2000	Y	87660	35	78457.14	89.50	99.922
Initial	53	400	20000	Y	87710	3300	77109.09	87.91	99.993
Initial	54	400	60000	Y	87720	3300	74309.09	84.72	99.979
Initial	55	600	5	Y	97130	35	39818.00	41.00	99.982
Initial	56	600	194	Y	97130	35	84972.00	87.49	99.982
Initial	57	600	500	Y	97130	35	86485.71	89.04	99.982
Initial	58	600	2000	Y	97330	35	86971.43	89.37	99.930
Initial	59	600	20000	Y	97390	3300	85927.27	88.23	99.994
Initial	60	600	60000	Y	97400	3300	82963.64	85.19	99.981
Initial	61	800	5	Y	102860	35	42150.29	40.98	99.978
Initial	62	800	194	Y	102860	35	89949.49	87.45	99.978
Initial	63	800	500	Y	102860	35	91557.14	89.01	99.978
Initial	64	800	2000	Y	103020	35	92285.71	89.62	99.934
Initial	65	800	20000	Y	103080	3300	90915.15	88.20	99.994
Initial	66	800	60000	Y	103090	3300	87890.91	85.27	99.982
Initial	67	1000	5	Y	106640	35	43662.00	40.95	99.973
Initial	68	1000	194	Y	106640	35	93175.43	87.37	99.973
Initial	69	1000	500	Y	106640	35	94857.14	88.96	99.973
Initial	70	1000	2000	Y	106770	35	95542.86	89.51	99.920
Initial	71	1000	20000	Y	106830	750	94480.00	88.44	99.974
Initial	72	1000	60000	Y	106830	750	91840.00	85.99	99.924

Table 27. Raw Experimental Results in Tabular Form (Part 3 of 5)

Type	Run	TF Len (bytes)	SP Len (bytes)	RS	SP Data Rate (Bps)	Sim Length (sec)	Throughput (Bps)	SP Data Quality (%)	Channel Utilization (%)
ATM	73	179	173	N	115820	35	101573.76	87.70	99.995
Second	74	41	50	N	94740	35	77553.43	81.86	99.998
Second	75	41	100	N	95390	35	81828.57	85.78	99.996
Second	76	41	150	N	95710	35	83322.00	87.06	99.995
Second	77	200	50	N	116720	35	94334.00	80.82	99.995
Second	78	200	100	N	116720	35	99589.14	85.32	99.995
Second	79	200	150	N	116720	35	101400.86	86.88	99.995
Second	80	400	50	N	120720	35	96791.72	80.18	99.991
Second	81	400	100	N	120720	35	102242.28	84.69	99.991
Second	82	400	150	N	120720	35	104137.70	86.26	99.991
Second	83	600	50	N	122110	35	97570.00	79.90	99.986
Second	84	600	100	N	122110	35	103069.70	84.41	99.986
Second	85	600	150	N	122110	35	104946.86	85.95	99.986
Second	86	800	50	N	122820	35	97761.43	79.60	99.981
Second	87	800	100	N	122820	35	103251.42	84.07	99.981
Second	88	800	150	N	122820	35	105160.26	85.62	99.981
Second	89	1000	50	N	123250	35	97872.28	79.41	99.977
Second	90	1000	100	N	123250	35	103295.40	83.81	99.977
Second	91	1000	150	N	123250	35	105297.40	85.44	99.977
Second	92	41	50	Y	24165	35	19512.86	80.75	99.990
Second	93	41	100	Y	24205	35	20608.57	85.15	99.986
Second	94	41	150	Y	24226	35	21000.00	86.69	99.981
Second	95	200	50	Y	67170	35	54275.71	80.81	99.992
Second	96	200	100	Y	67170	35	57340.00	85.37	99.992
Second	97	200	150	Y	67170	35	58435.71	87.00	99.992
Second	98	400	50	Y	87380	35	70455.71	80.63	99.987
Second	99	400	100	Y	87380	35	74434.29	85.19	99.987
Second	100	400	150	Y	87380	35	75865.71	86.83	99.987
Second	101	600	50	Y	97130	35	78208.57	80.52	99.982
Second	102	600	100	Y	97130	35	82631.43	85.07	99.982
Second	103	600	150	Y	97130	35	84214.29	86.71	99.982
Second	104	800	50	Y	102860	35	82791.43	80.49	99.978
Second	105	800	100	Y	102860	35	87471.43	85.04	99.978
Second	106	800	150	Y	102860	35	89147.14	86.67	99.978
Second	107	1000	50	Y	106640	35	85761.43	80.42	99.973
Second	108	1000	100	Y	106640	35	90608.57	84.97	99.973
Second	109	1000	150	Y	106640	35	92344.29	86.60	99.973

Table 28. Raw Experimental Results in Tabular Form (Part 4 of 5)

Type	Run	TF Len (bytes)	SP Len (bytes)	RS	SP Data Rate (Bps)	Sim Length (sec)	Throughput (Bps)	SP Data Quality (%)	Channel Utilization (%)
Third	110	41	300	N	96200	35	84723.43	88.07	99.990
Third	111	41	1000	N	96540	35	85068.57	88.14	99.970
Third	112	41	6000	N	96670	35	84000.00	87.03	99.822
Third	113	200	300	N	117320	35	103138.26	87.91	99.990
Third	114	200	1000	N	117720	35	103885.70	88.25	99.971
Third	115	200	6000	N	117890	35	102617.14	87.13	99.850
Third	116	400	300	N	120720	35	105963.44	87.78	99.991
Third	117	400	1000	N	121140	35	106765.72	88.15	99.972
Third	118	400	6000	N	121320	35	105565.72	87.10	99.849
Third	119	600	300	N	122110	35	106880.56	87.53	99.986
Third	120	600	1000	N	122330	35	107708.58	88.06	99.972
Third	121	600	6000	N	122510	35	107005.70	87.42	99.846
Third	122	800	300	N	122820	35	107117.16	87.22	99.981
Third	123	800	1000	N	122990	35	107994.28	87.82	99.963
Third	124	800	6000	N	123110	35	107108.60	87.02	99.852
Third	125	1000	300	N	123250	35	107364.00	87.11	99.977
Third	126	1000	1000	N	123390	35	108360.00	87.83	99.954
Third	127	1000	6000	N	123480	35	107519.98	87.11	99.838
Third	128	41	300	Y	24258	35	21394.29	88.20	99.961
Third	129	41	1000	Y	24280	35	21628.57	89.16	99.879
Third	130	41	6000	Y	24287	35	21428.57	88.65	99.291
Third	131	200	300	Y	67370	35	59571.43	88.43	99.983
Third	132	200	1000	Y	67500	35	60314.29	89.37	99.949
Third	133	200	6000	Y	67555	35	59828.57	88.58	99.738
Third	134	400	300	Y	87380	35	77322.86	88.49	99.987
Third	135	400	1000	Y	87610	35	78342.86	89.43	99.961
Third	136	400	6000	Y	87700	35	78171.43	89.24	99.792
Third	137	600	300	Y	97130	35	85842.86	88.39	99.982
Third	138	600	1000	Y	97260	35	86942.86	89.39	99.965
Third	139	600	6000	Y	97380	35	86742.86	89.08	99.806

Table 29. Raw Experimental Results in Tabular Form (Part 5 of 5)

Type	Run	TF Len (bytes)	SP Len (bytes)	RS	SP Data Rate (Bps)	Sim Length (sec)	Throughput (Bps)	SP Data Quality (%)	Channel Utilization (%)
Third	140	800	300	Y	102860	35	90874.29	88.35	99.978
Third	141	800	1000	Y	102980	35	92057.14	89.40	99.956
Third	142	800	6000	Y	103060	35	91885.71	89.18	99.823
Third	143	1000	300	Y	106640	35	94131.43	88.27	99.973
Third	144	1000	1000	Y	106740	35	95342.86	89.34	99.947
Third	145	1000	6000	Y	106810	35	95314.29	89.25	99.813
Third	146	41	700	N	96480	35	85164.00	88.29	99.978
Third	147	41	1400	N	96580	35	84992.00	88.02	99.958
Third	148	200	700	N	117620	35	103772.00	88.24	99.981
Third	149	200	1400	N	117770	35	103704.00	88.06	99.961
Third	150	400	700	N	121040	35	106684.00	88.14	99.981
Third	151	400	1400	N	121200	35	106672.00	88.04	99.962
Third	152	600	700	N	122330	35	107672.00	88.02	99.972
Third	153	600	1400	N	122400	35	107624.00	87.96	99.958
Third	154	800	700	N	122820	35	107996.00	87.94	99.981
Third	155	800	1400	N	122990	35	108144.00	87.95	99.963
Third	156	1000	700	N	123250	35	108188.00	87.79	99.977
Third	157	1000	1400	N	123390	35	108264.00	87.76	99.954
Third	158	41	700	Y	24275	35	21600.00	89.04	99.913
Third	159	41	1400	Y	24283	35	21600.00	88.96	99.831
Third	160	200	700	Y	67470	35	60200.00	89.24	99.966
Third	161	200	1400	Y	67520	35	60360.00	89.45	99.932
Third	162	400	700	Y	87550	35	78140.00	89.26	99.974
Third	163	400	1400	Y	87635	35	78480.00	89.59	99.948
Third	164	600	700	Y	97260	35	86800.00	89.25	99.965
Third	165	600	1400	Y	97310	35	87040.00	89.47	99.947
Third	166	800	700	Y	102860	35	91860.00	89.32	99.978
Third	167	800	1400	Y	102980	35	92160.00	89.51	99.956
Third	168	1000	700	Y	106640	35	95160.00	89.23	99.973
Third	169	1000	1400	Y	106740	35	95480.00	89.47	99.947

Table 30. Selected Throughput Results Sorted By Source Packet Payload Length

NO RS

TF Len (bytes)	Throughput (Bps)	SPLen = 5 bytes
41	39514.29	
200	48070.49	
400	49283.17	
600	49698.43	
800	49809.97	
1000	49856.57	

TF Len (bytes)	Throughput (Bps)	SP Len = 194 bytes
41	84006.43	
200	102609.38	
400	105274.38	
600	106076.98	
800	106272.08	
1000	106389.60	

TF Len (bytes)	Throughput (Bps)	SP Len = 500 bytes
41	85194.28	
200	103762.88	
400	106471.42	
600	107445.70	
800	107751.42	
1000	107951.42	

TF Len (bytes)	Throughput (Bps)	SP Len = 1000 bytes
41	85068.57	
200	103885.70	
400	106765.72	
600	107708.58	
800	107994.28	
1000	108360.00	

TF Len (bytes)	Throughput (Bps)	SP Len = 2000 bytes
41	84868.57	
200	103588.56	
400	106422.88	
600	107542.88	
800	107931.44	
1000	108022.86	

TF Len (bytes)	Throughput (Bps)	SP Len = 20000 bytes
41	82803.70	
200	101430.30	
400	104556.38	
600	105572.14	
800	105993.94	
1000	106213.34	

TF Len (bytes)	Throughput (Bps)	SP Len = 60000 bytes
41	78900.00	
200	97530.91	
400	100290.90	
600	101585.46	
800	101861.80	
1000	102352.00	

RS

TF Len (bytes)	Throughput (Bps)	SP Len = 5 bytes
41	9936.00	
200	27633.14	
400	35869.71	
600	39818.00	
800	42150.29	
1000	43662.00	

TF Len (bytes)	Throughput (Bps)	SP Len = 194 bytes
41	21179.26	
200	58970.46	
400	76546.86	
600	84972.00	
800	89949.49	
1000	93175.43	

TF Len (bytes)	Throughput (Bps)	SP Len = 500 bytes
41	21528.57	
200	60000.00	
400	77928.57	
600	86485.71	
800	91557.14	
1000	94857.14	

TF Len (bytes)	Throughput (Bps)	SP Len =1400 bytes
41	21600.00	
200	60360.00	
400	78480.00	
600	87040.00	
800	92160.00	
1000	95480.00	

TF Len (bytes)	Throughput (Bps)	SP Len = 2000 bytes
41	21542.86	
200	60342.86	
400	78457.14	
600	86971.43	
800	92285.71	
1000	95542.86	

TF Len (bytes)	Throughput (Bps)	SP Len = 20000 bytes
41	20383.33	
200	59127.27	
400	77109.09	
600	85927.27	
800	90915.15	
1000	94480.00	

TF Len (bytes)	Throughput (Bps)	SP Len = 60000 bytes
41	18411.11	
200	56327.27	
400	74309.09	
600	82963.64	
800	87890.91	
1000	91840.00	

Table 31. Selected Throughput Results Sorted By Transfer Frame Length (Part 1 of 2)

No RS

SP Len (bytes)	Throughput (Bps)	TF Len = 41bytes
5	39514.29	
50	77553.43	
100	81828.57	
150	83322.00	
194	84006.43	
500	85194.28	
700	85164.00	
1000	85068.57	
1400	84992.00	
2000	84868.57	
20000	82803.70	
60000	78900.00	

RS

SP Len (bytes)	Throughput (Bps)	TF Len = 41 bytes
5	9936.00	
50	19512.86	
100	20608.57	
150	21000.00	
194	21179.26	
500	21528.57	
700	21600.00	
1000	21628.57	
1400	21600.00	
2000	21542.86	
20000	20383.33	
60000	18411.11	

SP Len (bytes)	Throughput (Bps)	TF Len = 200 bytes
5	48070.49	
50	94334.00	
100	99589.14	
150	101400.86	
194	102609.38	
500	103762.88	
700	103772.00	
1000	103885.70	
1400	103704.00	
2000	103588.56	
20000	101430.30	
60000	97530.91	

SP Len (bytes)	Throughput (Bps)	TF Len = 200 bytes
5	27633.14	
50	54275.71	
100	57340.00	
150	58435.71	
194	58970.46	
500	60000.00	
700	60200.00	
1000	60314.29	
1400	60360.00	
2000	60342.86	
20000	59127.27	
60000	56327.27	

SP Len (bytes)	Throughput (Bps)	TF Len = 400 bytes
5	49283.17	
50	96791.72	
100	102242.28	
150	104137.70	
194	105274.38	
500	106471.42	
700	106684.00	
1000	106765.72	
1400	106672.00	
2000	106422.88	
20000	104556.38	
60000	100290.90	

SP Len (bytes)	Throughput (Bps)	TF Len = 400 bytes
5	35869.71	
50	70455.71	
100	74434.29	
150	75865.71	
194	76546.86	
500	77928.57	
700	78140.00	
1000	78342.86	
1400	78480.00	
2000	78457.14	
20000	77109.09	
60000	74309.09	

Table 32. Selected Throughput Results Sorted By Transfer Frame Length (Part 2 of 2)

NO RS

SP Len (bytes)	Throughput (Bps)	TF Len = 600 bytes
5	49698.43	
50	97570.00	
100	103069.70	
150	104946.86	
194	106076.98	
500	107445.70	
700	107672.00	
1000	107708.58	
1400	107624.00	
2000	107542.88	
20000	105572.14	
60000	101585.46	

SP Len (bytes)	Throughput (Bps)	TF Len = 800 bytes
5	49809.97	
50	97761.43	
100	103251.42	
150	105160.26	
194	106272.08	
500	107751.42	
700	107996.00	
1000	107994.28	
1400	108144.00	
2000	107931.44	
20000	105993.94	
60000	101861.80	

SP Len (bytes)	Throughput (Bps)	TF Len = 1000 bytes
5	49856.57	
50	97872.28	
100	103295.40	
150	105297.40	
194	106389.60	
500	107951.42	
700	108188.00	
1000	108360.00	
1400	108264.00	
2000	108022.86	
20000	106213.34	
60000	102352.00	

RS

SP Len (bytes)	Throughput (Bps)	TFLen = 600 bytes
5	39818.00	
50	78208.57	
100	82631.43	
150	84214.29	
194	84972.00	
500	86485.71	
700	86800.00	
1000	86942.86	
1400	87040.00	
2000	86971.43	
20000	85927.27	
60000	82963.64	

SP Len (bytes)	Throughput (Bps)	TF Len = 800 bytes
5	42150.29	
50	82791.43	
100	87471.43	
150	89147.14	
194	89949.49	
500	91557.14	
700	91860.00	
1000	92057.14	
1400	92160.00	
2000	92285.71	
20000	90915.15	
60000	87890.91	

SP Len (bytes)	Throughput (Bps)	TFLen = 1000 bytes
5	43662.00	
50	85761.43	
100	90608.57	
150	92344.29	
194	93175.43	
500	94857.14	
700	95160.00	
1000	95342.86	
1400	95480.00	
2000	95542.86	
20000	94480.00	
60000	91840.00	

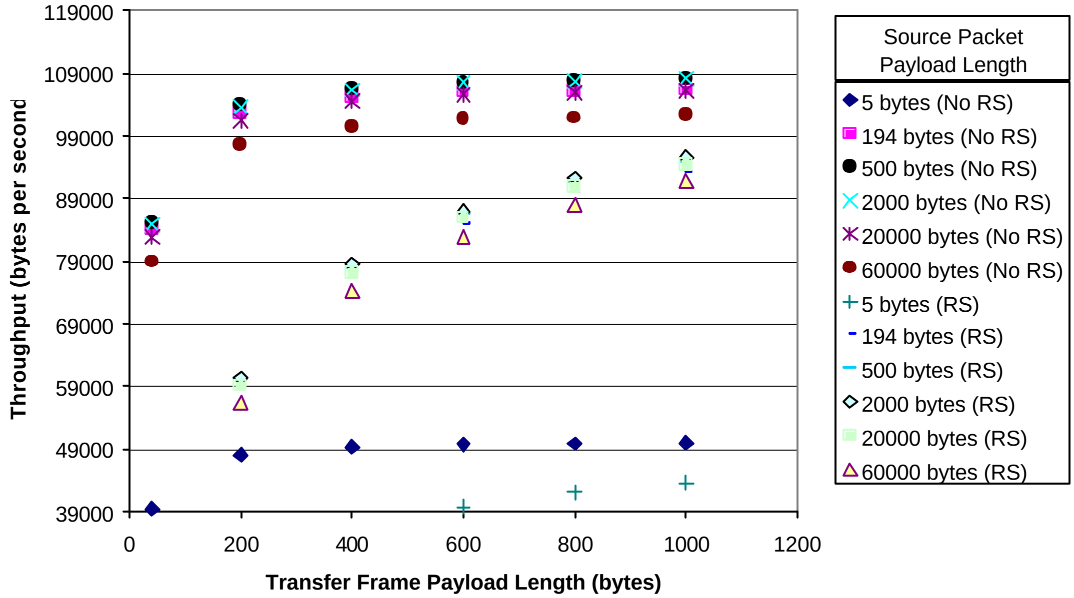


Figure 44. Throughput Variation With Transfer Frame Length In Graphical Format

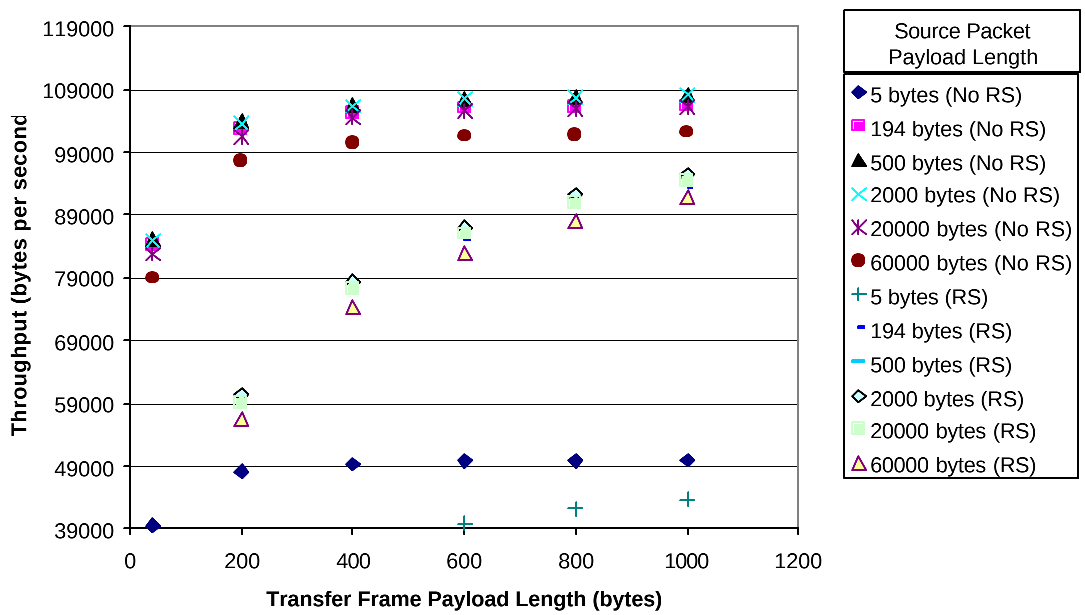


Figure 45. Throughput Variation With Source Packet Length In Graphical Format

Table 33. Selected Data Quality Results Sorted By Source Packet Length

NO RS

TF Len (bytes)	Data Quality (%)	SP Len = 5 bytes
41	42.55	
200	41.19	
400	40.83	
600	40.70	
800	40.56	
1000	40.45	

TF Len (bytes)	Data Quality (%)	SP Len = 194 bytes
41	87.59	
200	87.91	
400	87.21	
600	86.87	
800	86.53	
1000	86.32	

TF Len (bytes)	Data Quality (%)	SP Len = 500 bytes
41	88.39	
200	88.30	
400	87.97	
600	88.00	
800	87.74	
1000	87.59	

TF Len (bytes)	Data Quality (%)	SP Len = 1000 bytes
41	88.14	
200	88.25	
400	88.15	
600	88.06	
800	87.82	
1000	87.83	

TF Len (bytes)	Data Quality (%)	SP Len = 2000 bytes
41	87.88	
200	87.96	
400	87.81	
600	87.86	
800	87.73	
1000	87.52	

TF Len (bytes)	Data Quality (%)	SP Len = 20000 bytes
41	85.64	
200	86.02	
400	86.16	
600	86.15	
800	86.08	
1000	86.01	

TF Len (bytes)	Data Quality (%)	SP Len = 60000 bytes
41	81.60	
200	82.72	
400	82.65	
600	82.91	
800	82.72	
1000	82.92	

RS

TF Len (bytes)	Data Quality (%)	SP Len = 5 bytes
41	41.33	
200	41.14	
400	41.05	
600	41.00	
800	40.98	
1000	40.95	

TF Len (bytes)	Data Quality (%)	SP Len = 194 bytes
41	87.38	
200	87.80	
400	87.60	
600	87.49	
800	87.45	
1000	87.37	

TF Len (bytes)	Data Quality (%)	SP Len = 500 bytes
41	88.75	
200	88.98	
400	89.02	
600	89.04	
800	89.01	
1000	88.96	

TF Len (bytes)	Data Quality (%)	SP Len = 1400 bytes
41	88.96	
200	89.45	
400	89.59	
600	89.47	
800	89.51	
1000	89.47	

TF Len (bytes)	Data Quality (%)	SP Len = 2000 bytes
41	88.92	
200	89.42	
400	89.50	
600	89.37	
800	89.62	
1000	89.51	

TF Len (bytes)	Data Quality (%)	SP Len = 20000 bytes
41	83.93	
200	87.51	
400	87.91	
600	88.23	
800	88.20	
1000	88.44	

TF Len (bytes)	Data Quality (%)	SP Len = 60000 bytes
41	75.82	
200	83.37	
400	84.72	
600	85.19	
800	85.27	
1000	85.99	

Table 34. Selected Data Quality Results Sorted By Transfer Frame Length (Part 1 of 2)

No RS

SP Len (bytes)	Data Quality (%)	TF Len = 41 bytes
5	42.55	
50	81.86	
100	85.78	
150	87.06	
194	87.59	
300	88.07	
500	88.39	
700	88.29	
1000	88.14	
1400	88.02	
2000	87.88	
6000	87.03	
20000	85.64	
60000	81.60	

SP Len (bytes)	Data Quality (%)	TF Len = 200 bytes
5	41.19	
50	80.82	
100	85.32	
150	86.88	
194	87.91	
300	87.91	
500	88.30	
700	88.24	
1000	88.25	
1400	88.06	
2000	87.96	
6000	87.13	
20000	86.02	
60000	82.72	

SP Len (bytes)	Data Quality (%)	TFLen = 400 bytes
5	40.83	
50	80.18	
100	84.69	
150	86.26	
194	87.21	
300	87.78	
500	87.97	
700	88.14	
1000	88.15	
1400	88.04	
2000	87.81	
6000	87.10	
20000	86.16	
60000	82.65	

RS

SP Len (bytes)	Data Quality (%)	TF Len = 41 bytes
5	41.33	
50	80.75	
100	85.15	
150	86.69	
194	87.38	
300	88.20	
500	88.75	
700	89.04	
1000	89.16	
1400	88.96	
2000	88.92	
6000	88.65	
20000	83.93	
60000	75.82	

SP Len (bytes)	Data Quality (%)	TF Len = 200 bytes
5	41.14	
50	80.81	
100	85.37	
150	87.00	
194	87.80	
300	88.43	
500	88.98	
700	89.24	
1000	89.37	
1400	89.45	
2000	89.42	
6000	88.58	
20000	87.51	
60000	83.37	

SP Len (bytes)	Data Quality (%)	TFLen = 400 bytes
5	41.05	
50	80.63	
100	85.19	
150	86.83	
194	87.60	
300	88.49	
500	89.02	
700	89.26	
1000	89.43	
1400	89.59	
2000	89.50	
6000	89.24	
20000	87.91	
60000	84.72	

Table 35. Selected Data Quality Results Sorted By Transfer Frame Length (Part 2 of 2)

No RS

SP Len (bytes)	Data Quality (%)	TF Len = 600 bytes
5	40.70	
50	79.90	
100	84.41	
150	85.95	
194	86.87	
300	87.53	
500	88.00	
700	88.02	
1000	88.06	
1400	87.96	
2000	87.86	
6000	87.42	
20000	86.15	
60000	82.91	

SP Len (bytes)	Data Quality (%)	TF Len = 800 bytes
5	40.56	
50	79.60	
100	84.07	
150	85.62	
194	86.53	
300	87.22	
500	87.74	
700	87.94	
1000	87.82	
1400	87.95	
2000	87.73	
6000	87.02	
20000	86.08	
60000	82.72	

SP Len (bytes)	Data Quality (%)	TFLen = 1000 bytes
5	40.45	
50	79.41	
100	83.81	
150	85.44	
194	86.32	
300	87.11	
500	87.59	
700	87.79	
1000	87.83	
1400	87.76	
2000	87.52	
6000	87.11	
20000	86.01	
60000	82.92	

RS

SP Len (bytes)	Data Quality (%)	TF Len = 600 bytes
5	41.00	
50	80.52	
100	85.07	
150	86.71	
194	87.49	
300	88.39	
500	89.04	
700	89.25	
1000	89.39	
1400	89.47	
2000	89.37	
6000	89.08	
20000	88.23	
60000	85.19	

SP Len (bytes)	Data Quality (%)	TF Len = 800 bytes
5	40.98	
50	80.49	
100	85.04	
150	86.67	
194	87.45	
300	88.35	
500	89.01	
700	89.32	
1000	89.40	
1400	89.51	
2000	89.62	
6000	89.18	
20000	88.20	
60000	85.27	

SP Len (bytes)	Data Quality (%)	TFLen = 1000 bytes
5	40.95	
50	80.42	
100	84.97	
150	86.60	
194	87.37	
300	88.27	
500	88.96	
700	89.23	
1000	89.34	
1400	89.47	
2000	89.51	
6000	89.25	
20000	88.44	
60000	85.99	

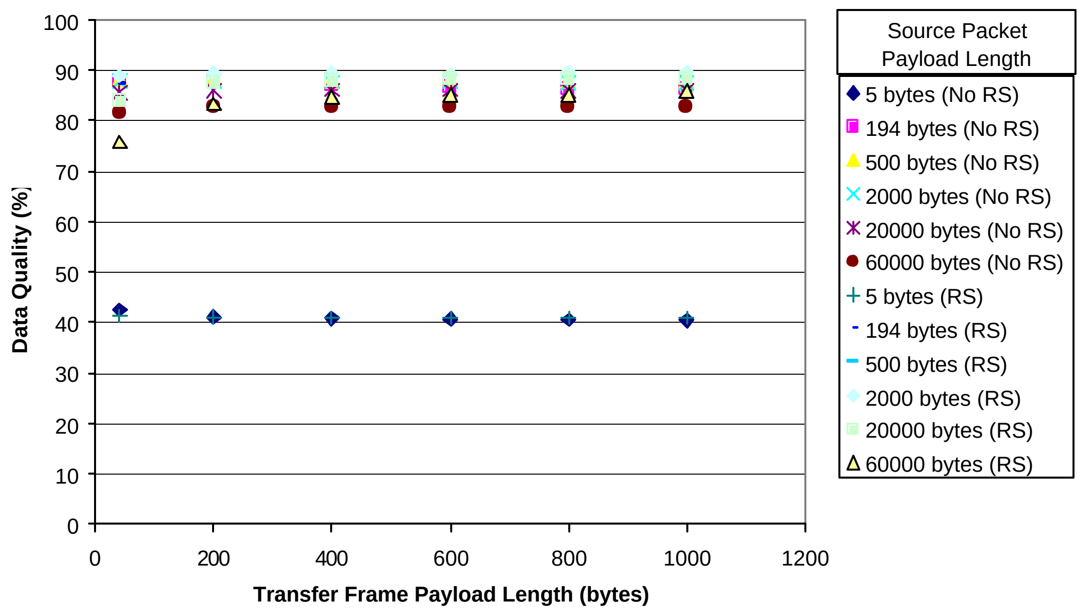


Figure 46. Data Quality Variation With Transfer Frame Length In Graphical Format

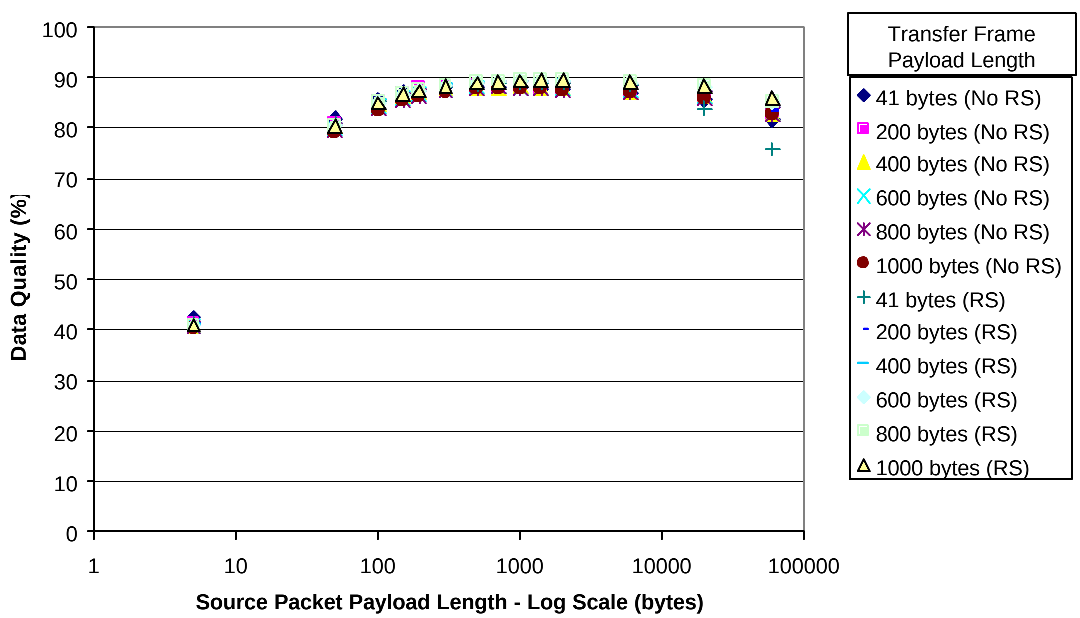


Figure 47. Data Quality Variation With Source Packet Length In Graphical Format

APPENDIX H - Raw Flight Test Data

This appendix lists the throughput, data quality, and channel utilization results from each flight test data run. Sample size varied given flight test conditions and time constraints. A representative confidence level was 80%, with throughput data accurate to within ±935 Bps and data quality accurate to within ±0.92 percentage points. Confidence and accuracy calculations are shown in Appendix E. The following tables and figures are provided in this appendix:

Table 36. Raw Flight Test Results in Tabular Form (Part 1 of 2)

Table 37. Raw Flight Test Results in Tabular Form (Part 2 of 2)

Table 38. Flight Test Throughput Results Sorted By Source Packet Length

Table 39. Flight Test Throughput Results Sorted By Transfer Frame Length

Figure 48. Flight Test Variation in Throughput With Transfer Frame Length

Figure 49. Flight Test Variation in Throughput With Source Packet Length

Table 40. Flight Test Data Quality Results Sorted By Source Packet Length

Table 41. Flight Test Data Quality Results Sorted By Transfer Frame Length

Figure 50. Flight Test Data Quality Variation With Transfer Frame Length

Figure 51. Flight Test Data Quality Variation With Source Packet Length

Table 36. Raw Flight Test Results in Tabular Form (Part 1 of 2)

Type	Run	TF Len (bytes)	SP Len (bytes)	RS	Run Length (sec)	Throughput (Bps)	SP Data Quality (%)
Initial	1	50	30	N	743	73047.62	90.81
Initial	2	50	194	N	711	91286.96	97.49
Initial	3	50	500	N	725	88852.41	96.43
Initial	4	50	2000	N	697	88370.16	93.02
Initial	5	50	20000	N	720	82694.44	88.71
Initial	6	50	60000	N	717	77991.63	77.54
Initial	7	200	30	N	707	78790.69	97.39
Initial	8	200	194	N	705	107250.35	96.59
Initial	9	200	500	N	742	108934.64	95.54
Initial	10	200	2000	N	719	108350.49	95.37
Initial	11	200	20000	N	725	102206.90	90.26
Initial	12	200	60000	N	723	96265.56	86.96
Initial	13	400	30	N	718	91869.07	92.95
Initial	14	400	194	N	715	113064.56	97.43
Initial	15	400	500	N	735	102923.13	90.43
Initial	16	400	2000	N	726	112662.87	95.08
Initial	17	400	20000	N	731	106183.31	90.26
Initial	18	400	60000	N	707	101669.02	88.35
Initial	19	600	30	N	711	97950.46	96.89
Initial	20	600	194	N	715	113958.86	97.14
Initial	21	600	500	N	716	112728.35	96.54
Initial	22	600	2000	N	745	111524.83	93.16
Initial	23	600	20000	N	726	97465.56	82.59
Initial	24	600	60000	N	720	100166.67	85.86
Initial	25	800	30	N	710	93640.52	92.16
Initial	26	800	194	N	729	115357.08	97.73
Initial	27	800	500	N	720	116551.39	97.29
Initial	28	800	2000	N	747	114000.00	90.13
Initial	29	800	20000	N	716	111759.78	93.22
Initial	30	800	60000	N	718	104958.22	89.52

Table 37. Raw Flight Test Results in Tabular Form (Part 2 of 2)

Type	Run	TF Len (bytes)	SP Len (bytes)	RS	Run Length (sec)	Throughput (Bps)	SP Data Quality (%)
Initial	31	1000	30	N	723	93083.11	91.34
Initial	32	1000	194	N	745	113640.25	95.97
Initial	33	1000	500	N	700	107037.14	89.77
Initial	34	1000	2000	N	732	114188.52	94.20
Initial	35	1000	20000	N	719	103282.34	86.67
Initial	36	1000	60000	N	729	91934.16	79.11
Initial	37	939	30	Y	709	83809.21	95.87
Initial	38	939	194	Y	713	95107.34	93.68
Initial	39	939	500	Y	719	90050.76	87.60
Initial	40	939	2000	Y	728	98320.66	95.01
Initial	41	939	20000	Y	710	84028.17	83.67
Initial	42	939	60000	Y	736	78505.43	79.39
Second	43	125	30	N	716	data invalid	data invalid
Second	44	125	194	N	730	104944.17	97.26
Second	45	125	500	N	731	103759.92	94.69
Second	46	125	2000	N	725	104733.79	96.10
Second	47	125	20000	N	703	data invalid	data invalid
Second	48	125	60000	N	712	data invalid	data invalid
ATM	49	198	192	N	724	107898.93	96.88
Second	50	300	100	N	727	102504.54	91.85
Second	51	300	350	N	725	103305.03	89.59
Second	52	300	750	N	712	110534.41	94.56
Second	53	300	1000	N	728	111145.60	94.92
Second	54	300	5000	N	731	109746.92	93.95
Second	55	300	40000	N	714	100112.04	87.77
Second	56	500	100	N	708	97677.82	96.40
Second	57	500	350	N	730	112508.70	95.19
Second	58	500	750	N	725	115038.62	96.55
Second	59	500	1000	N	721	114603.33	96.18
Second	60	500	5000	N	709	107912.55	90.81
Second	61	500	40000	N	731	103036.94	88.11

Table 38. Flight Test Throughput Results Sorted By Source Packet Length

NO RS

TF Len (bytes)	Throughput (Bps)	SPLen = 30 bytes
50	73047.62	
200	78790.69	
400	91869.07	
600	97950.46	
800	93640.52	
1000	93083.11	

RS

TF Len (bytes)	Throughput (Bps)	SP Len = 30 bytes
939	83809.21	

TF Len (bytes)	Throughput (Bps)	SP Len = 194 bytes
50	91286.96	
125	104944.17	
200	107250.35	
400	113064.56	
600	113958.86	
800	115357.08	
1000	113640.25	

TF Len (bytes)	Throughput (Bps)	SP Len = 194 bytes
939	95107.34	

TF Len (bytes)	Throughput (Bps)	SP Len = 500 bytes
50	88852.41	
125	103759.92	
200	108934.64	
400	102923.13	
600	112728.35	
800	116551.39	
1000	107037.14	

TF Len (bytes)	Throughput (Bps)	SP Len = 500 bytes
939	90050.76	

TF Len (bytes)	Throughput (Bps)	SP Len = 2000 bytes
50	88370.16	
125	104733.79	
200	108350.49	
400	112662.87	
600	111524.83	
800	114000.00	
1000	114188.52	

TF Len (bytes)	Throughput (Bps)	SP Len = 2000 bytes
939	98320.66	

TF Len (bytes)	Throughput (Bps)	SP Len = 20000 bytes
50	82694.44	
200	102206.90	
400	106183.31	
600	97465.56	
800	111759.78	
1000	103282.34	

TF Len (bytes)	Throughput (Bps)	SP Len = 20000 bytes
939	84028.17	

TF Len (bytes)	Throughput (Bps)	SP Len = 60000 bytes
50	77991.63	
200	96265.56	
400	101669.02	
600	100166.67	
800	104958.22	
1000	91934.16	

TF Len (bytes)	Throughput (Bps)	SP Len = 60000 bytes
939	78505.43	

Table 39. Flight Test Throughput Results Sorted By Transfer Frame Length

No RS

SP Len (bytes)	Throughput (Bps)	TF Len = 50 bytes
30	73047.62	
194	91286.96	
500	88852.41	
2000	88370.16	
20000	82694.44	
60000	77991.63	

RS

SP Len (bytes)	Throughput (Bps)	TF Len = 939 bytes
30	83809.21	
194	95107.34	
500	90050.76	
2000	98320.66	
20000	84028.17	
60000	78505.43	

SP Len (bytes)	Throughput (Bps)	TF Len = 200 bytes
30	78790.69	
194	107250.35	
500	108934.64	
2000	108350.49	
20000	102206.90	
60000	96265.56	

SP Len (bytes)	Throughput (Bps)	TF Len = 400 bytes
30	91869.07	
194	113064.56	
500	102923.13	
2000	112662.87	
20000	106183.31	
60000	101669.02	

SP Len (bytes)	Throughput (Bps)	TF Len = 600 bytes
30	97950.46	
194	113958.86	
500	112728.35	
2000	111524.83	
20000	97465.56	
60000	100166.67	

SP Len (bytes)	Throughput (Bps)	TF Len = 800 bytes
30	93640.52	
194	115357.08	
500	116551.39	
2000	114000.00	
20000	111759.78	
60000	104958.22	

SP Len (bytes)	Throughput (Bps)	TF Len = 1000 bytes
30	93083.11	
194	113640.25	
500	107037.14	
2000	114188.52	
20000	103282.34	
60000	91934.16	

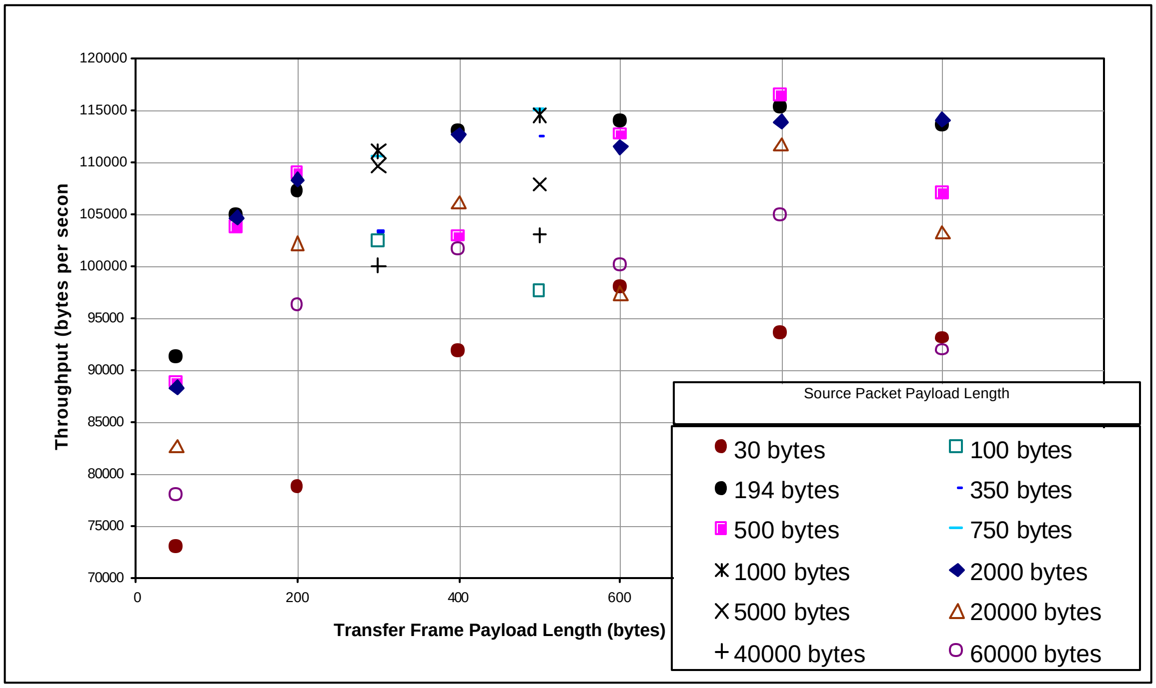


Figure 48. **Flight Test Variation in Throughput With Tr ansfer Frame Length**

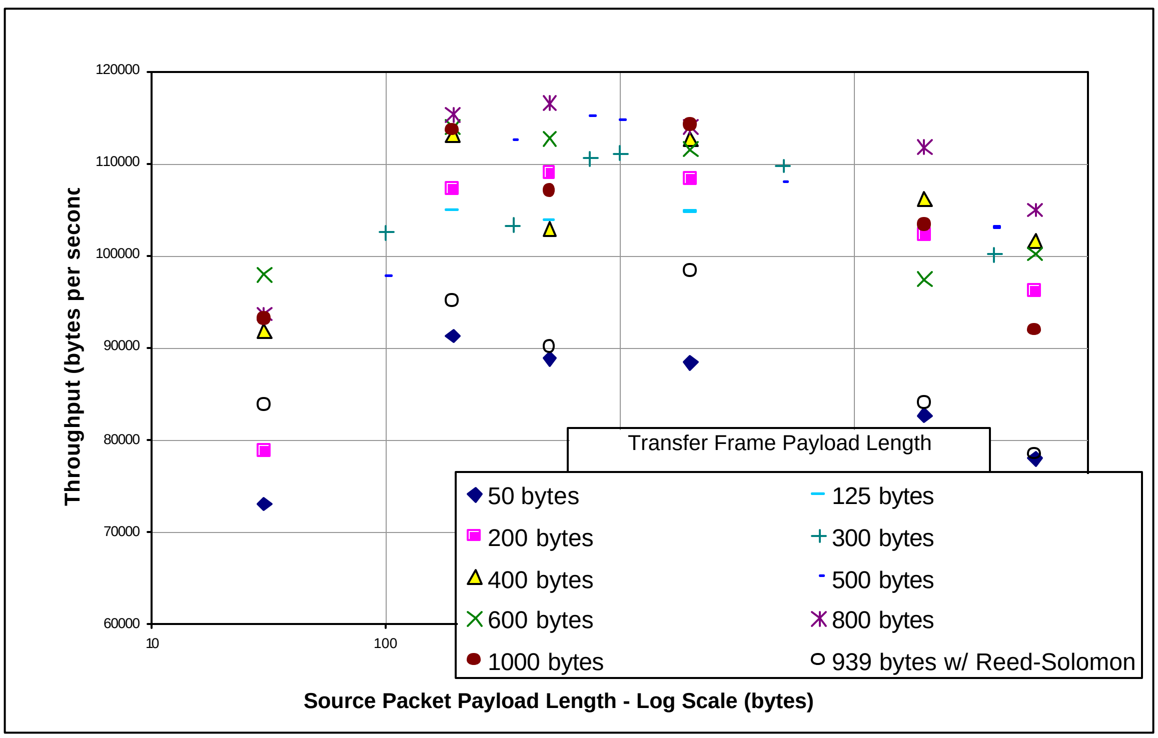


Figure 49. Flight Test Variation in Throughput With Source Packet Length

Table 40. Flight Test Data Quality Results Sorted By Source Packet Length

NO RS

TF Len (bytes)	Data Quality (%)	SP Len = 30 bytes
50	90.81	
200	97.39	
400	92.95	
600	96.89	
800	92.16	
1000	91.34	

RS

TF Len (bytes)	Data Quality (%)	SP Len = 30 bytes
939	95.87	

NO RS

TF Len (bytes)	Data Quality (%)	SP Len = 194 bytes
50	97.49	
125	97.26	
200	96.59	
400	97.43	
600	97.14	
800	97.73	
1000	95.97	

RS

TF Len (bytes)	Data Quality (%)	SP Len = 194 bytes
939	93.68	

NO RS

TF Len (bytes)	Data Quality (%)	SP Len = 500 bytes
50	96.43	
125	94.69	
200	95.54	
400	90.43	
600	96.54	
800	97.29	
1000	89.77	

RS

TF Len (bytes)	Data Quality (%)	SP Len = 500 bytes
939	87.60	

NO RS

TF Len (bytes)	Data Quality (%)	SP Len = 2000 bytes
50	93.02	
125	96.10	
200	95.37	
400	95.08	
600	93.16	
800	90.13	
1000	94.20	

RS

TF Len (bytes)	Data Quality (%)	SP Len =2000 bytes
939	95.01	

NO RS

TF Len (bytes)	Data Quality (%)	SP Len = 20000 bytes
50	88.71	
200	90.26	
400	90.26	
600	82.59	
800	93.22	
1000	86.67	

RS

TF Len (bytes)	Data Quality (%)	SP Len =20000 bytes
939	83.67	

NO RS

TF Len (bytes)	Data Quality (%)	SP Len = 60000 bytes
50	77.54	
200	86.96	
400	88.35	
600	85.86	
800	89.52	
1000	79.11	

RS

TF Len (bytes)	Data Quality (%)	SP Len =60000 bytes
939	79.39	

Table 41. Flight Test Data Quality Results Sorted By Transfer Frame Length

No RS

SP Len (bytes)	Data Quality (%)	TF Len = 50 bytes
30	90.81	
194	97.49	
500	96.43	
2000	93.02	
20000	88.71	
60000	77.54	

SP Len (bytes)	Data Quality (%)	TF Len = 200 bytes
30	97.39	
194	96.59	
500	95.54	
2000	95.37	
20000	90.26	
60000	86.96	

SP Len (bytes)	Data Quality (%)	TF Len = 400 bytes
30	92.95	
194	97.43	
500	90.43	
2000	95.08	
20000	90.26	
60000	88.35	

SP Len (bytes)	Data Quality (%)	TF Len = 600 bytes
30	96.89	
194	97.14	
500	96.54	
2000	93.16	
20000	82.59	
60000	85.86	

SP Len (bytes)	Data Quality (%)	TF Len = 800 bytes
30	92.16	
194	97.73	
500	97.29	
2000	90.13	
20000	93.22	
60000	89.52	

SP Len (bytes)	Data Quality (%)	TF Len = 1000 bytes
30	91.34	
194	95.97	
500	89.77	
2000	94.20	
20000	86.67	
60000	79.11	

RS

SP Len (bytes)	Data Quality (%)	TF Len = 939 bytes
30	95.87	
194	93.68	
500	87.60	
2000	95.01	
20000	83.67	
60000	79.39	

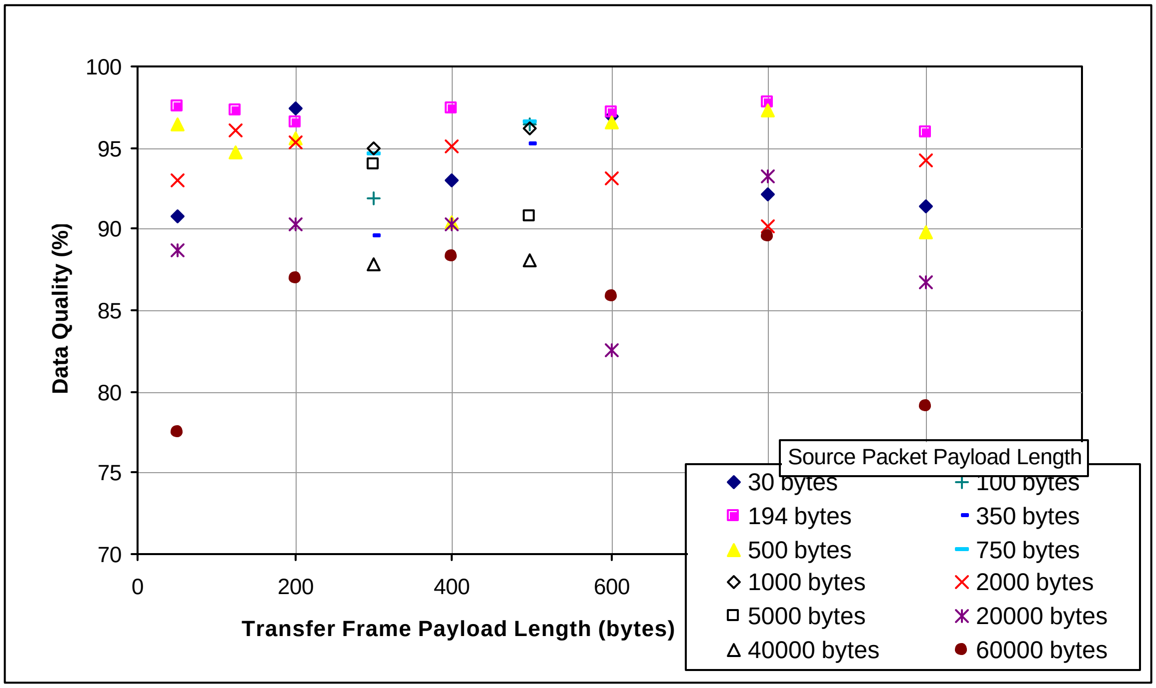


Figure 50. **Flight Test Data Quality Variation With Transfer Frame Length**

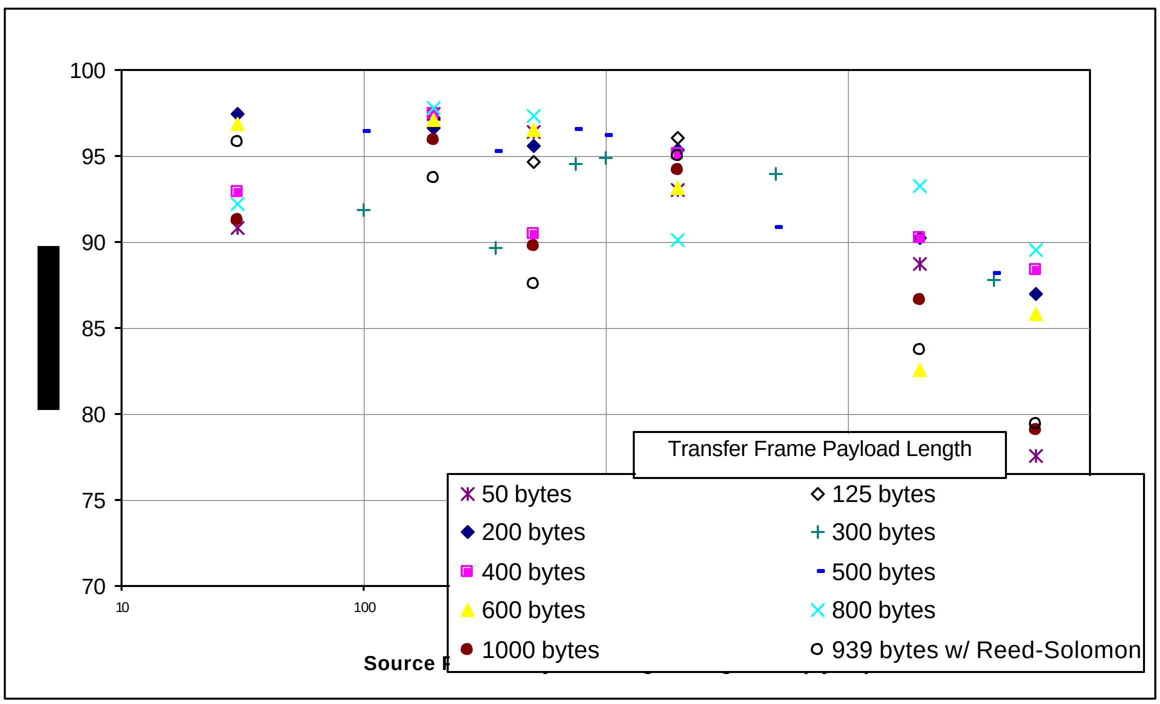


Figure 51. Flight Test Data Quality Variation With Source Packet Length

APPENDIX I - Raw Simulation Data (95-4-1 Channel Model)

This appendix lists the throughput, data quality, and channel utilization results from each simulation run using the 95-4-1 channel model. Values shown are the arithmetic mean of data from five samples. This sample size yielded a worst-case confidence of 90%. Throughput data is accurate to within ±127 Bps. Data quality data is accurate to within ±0.103 percentage points. Confidence and accuracy calculations are shown in Appendix E. The following tables are provided in this appendix:

Table 42. Raw Experimental Results in Tabular Form (Part 1 of 3)

Type	Run	TF Len (bytes)	SP Len (bytes)	RS	SP Data Rate (Bps)	Sim Length (sec)	Throughput (Bps)	SP Data Quality (%)	Channel Utilization (%)
Initial	1	41	5	N	92865	80	40531.69	45.23	99.999
Initial	2	41	194	N	95910	80	84816.80	91.75	99.997
Initial	3	41	500	N	96390	80	85131.25	91.64	99.993
Initial	4	41	2000	N	96620	80	87675.00	91.33	99.974
Initial	5	41	20000	N	96690	3000	86126.67	89.72	99.993
Initial	6	41	60000	N	96700	10800	85876.67	88.81	99.994
Initial	7	200	5	N	116720	80	50611.63	43.77	99.998
Initial	8	200	194	N	116720	80	108028.90	93.42	99.998
Initial	9	200	500	N	117520	80	109643.80	94.18	99.994
Initial	10	200	2000	N	117810	80	109675.00	93.98	99.977
Initial	11	200	20000	N	117910	755	108264.90	92.70	99.977
Initial	12	200	60000	N	117920	3000	104420.00	89.39	99.983
Initial	13	400	5	N	120720	80	52225.88	43.47	99.996
Initial	14	400	194	N	120720	80	111457.90	92.77	99.996
Initial	15	400	500	N	121040	80	113456.30	94.19	99.992
Initial	16	400	2000	N	121250	80	113825.00	94.34	99.975
Initial	17	400	20000	N	121350	80	111750.00	92.55	99.790
Initial	18	400	60000	N	121350	755	109668.90	90.85	99.934
Initial	19	600	5	N	122110	80	52775.06	43.36	99.994
Initial	20	600	194	N	122110	80	112631.60	92.53	99.994
Initial	21	600	500	N	122110	80	114643.80	94.19	99.994
Initial	22	600	2000	N	122440	80	115225.00	94.43	99.976
Initial	23	600	20000	N	122540	80	113000.00	92.62	99.792
Initial	24	600	60000	N	122540	755	110304.60	90.36	99.935
Initial	25	800	5	N	122820	80	53058.13	43.31	99.992
Initial	26	800	194	N	122820	80	113237.80	92.43	99.992
Initial	27	800	500	N	122820	80	115318.80	94.12	99.992
Initial	28	800	2000	N	123040	80	115975.00	94.50	99.976
Initial	29	800	20000	N	123140	80	113750.00	92.67	99.789
Initial	30	800	60000	N	123150	755	111178.80	90.55	99.935
Initial	31	1000	5	N	123250	80	53220.63	43.27	99.990
Initial	32	1000	194	N	123250	80	113574.90	92.33	99.990
Initial	33	1000	500	N	123250	80	115593.80	93.97	99.990
Initial	34	1000	2000	N	123430	80	116425.00	94.52	99.970
Initial	35	1000	20000	N	123500	80	113750.00	92.29	99.787
Initial	36	1000	60000	N	123510	755	111576.20	90.52	99.935

Table 43. Raw Experimental Results in Tabular Form (Part 2 of 3)

Type	Run	TF Len (bytes)	SP Len (bytes)	RS	SP Data Rate (Bps)	Sim Length (sec)	Throughput (Bps)	SP Data Quality (%)	Channel Utilization (%)
Initial	37	41	5	Y	24040	80	10497.56	44.08	99.998
Initial	38	41	194	Y	24240	80	22385.17	93.23	99.989
Initial	39	41	500	Y	24270	80	22787.50	94.80	99.973
Initial	40	41	2000	Y	24285	80	22750.00	94.59	99.897
Initial	41	41	20000	Y	24288	3000	21646.67	89.99	99.973
Initial	42	41	60000	Y	24288	10800	19661.11	81.73	99.977
Initial	43	200	5	Y	67170	80	29316.75	43.88	99.996
Initial	44	200	194	Y	67170	80	62562.57	93.64	99.996
Initial	45	200	500	Y	67432	80	63693.75	94.97	99.989
Initial	46	200	2000	Y	67530	80	64000.00	95.31	99.959
Initial	47	200	20000	Y	67565	755	63046.36	93.85	99.960
Initial	48	200	60000	Y	67565	3000	60300.00	89.73	99.970
Initial	49	400	5	Y	87380	80	38129.13	43.79	99.994
Initial	50	400	194	Y	87380	80	81368.45	93.44	99.994
Initial	51	400	500	Y	87550	80	82850.00	94.96	99.989
Initial	52	400	2000	Y	87660	80	83350.00	95.42	99.966
Initial	53	400	20000	Y	87710	80	82000.00	93.98	99.709
Initial	54	400	60000	Y	87720	755	80105.96	91.72	99.909
Initial	55	600	5	Y	97130	80	42371.25	43.74	99.992
Initial	56	600	194	Y	97130	80	90420.98	93.33	99.992
Initial	57	600	500	Y	97130	80	92075.00	95.05	99.992
Initial	58	600	2000	Y	97330	80	92700.00	95.54	99.969
Initial	59	600	20000	Y	97390	80	91250.00	94.07	99.738
Initial	60	600	60000	Y	97400	755	89086.09	91.73	99.918
Initial	61	800	5	Y	102860	80	44863.38	43.71	99.990
Initial	62	800	194	Y	102860	80	95739.00	93.27	99.990
Initial	63	800	500	Y	102860	80	97481.25	94.96	99.990
Initial	64	800	2000	Y	103020	80	98250.00	95.57	99.971
Initial	65	800	20000	Y	103080	80	96500.00	93.92	99.748
Initial	66	800	60000	Y	103090	755	95682.12	93.04	99.922
Initial	67	1000	5	Y	106640	80	46494.06	43.68	99.988
Initial	68	1000	194	Y	106640	80	99218.88	93.20	99.988
Initial	69	1000	500	Y	106640	80	101025.00	94.90	99.988
Initial	70	1000	2000	Y	106770	80	101800.00	95.52	99.965
Initial	71	1000	20000	Y	106830	80	100500.00	94.37	99.754
Initial	72	1000	60000	Y	106830	755	98781.46	92.62	99.924

Table 44. Raw Experimental Results in Tabular Form (Part 3 of 3)

Type	Run	TF Len (bytes)	SP Len (bytes)	RS	SP Data Rate (Bps)	Sim Length (sec)	Throughput (Bps)	SP Data Quality (%)	Channel Utilization (%)
ATM	73	179	173	N	115820	80	107884.80	93.37	98.865
Second	74	41	1000	N	96540	80	85050.00	91.43	99.987
Second	75	200	1000	N	117720	80	109612.50	94.00	99.987
Second	76	400	1000	N	121140	80	113900.00	94.48	99.988
Second	77	600	1000	N	122330	80	115162.50	94.45	99.988
Second	78	800	1000	N	122990	80	115862.50	94.45	99.984
Second	79	1000	1000	N	123390	80	116237.50	94.40	99.980
Second	80	41	1000	Y	24280	80	22800.00	94.80	99.947
Second	81	200	1000	Y	67500	80	64000.00	95.33	99.978
Second	82	400	1000	Y	87610	80	83312.50	95.43	99.983
Second	83	600	1000	Y	97260	80	92575.00	95.44	99.985
Second	84	800	1000	Y	102980	80	98050.00	95.43	99.981
Second	85	1000	1000	Y	106740	80	101587.50	95.34	99.977
Second	86	41	6000	N	96670	80	86925.00	90.62	99.922
Second	87	200	6000	N	117890	80	108975.00	93.32	99.934
Second	88	400	6000	N	121320	80	113325.00	93.91	99.934
Second	89	600	6000	N	122510	80	114825.00	94.04	99.933
Second	90	800	6000	N	123110	80	115425.00	94.01	99.935
Second	91	1000	6000	N	123480	80	115875.00	94.04	99.929
Second	92	41	6000	Y	24287	80	22425.00	93.44	99.690
Second	93	200	6000	Y	67555	80	63750.00	94.97	99.885
Second	94	400	6000	Y	87700	80	83100.00	95.11	99.909
Second	95	600	6000	Y	97380	80	92475.00	95.21	99.915
Second	96	800	6000	Y	103060	80	98100.00	95.40	99.922
Second	97	1000	6000	Y	106810	80	101550.00	95.29	99.918

Table 45. Selected Throughput Results Sorted By Source Packet Payload Length

NO RS

TF Len (bytes)	Throughput (Bps)	SPLen = 5 bytes
41	40531.69	
200	50611.63	
400	52225.88	
600	52775.06	
800	53058.13	
1000	53220.63	

TF Len (bytes)	Throughput (Bps)	SP Len = 194 bytes
41	84816.80	
200	108028.90	
400	111457.90	
600	112631.60	
800	113237.80	
1000	113574.90	

TF Len (bytes)	Throughput (Bps)	SP Len = 500 bytes
41	85131.25	
200	109643.80	
400	113456.30	
600	114643.80	
800	115318.80	
1000	115593.80	

TF Len (bytes)	Throughput (Bps)	SP Len = 2000 bytes
41	87675.00	
200	109675.00	
400	113825.00	
600	115225.00	
800	115975.00	
1000	116425.00	

TF Len (bytes)	Throughput (Bps)	SP Len = 20000 bytes
41	86126.67	
200	108264.90	
400	111750.00	
600	113000.00	
800	113750.00	
1000	113750.00	

TF Len (bytes)	Throughput (Bps)	SP Len = 60000 bytes
41	85876.67	
200	104420.00	
400	109668.90	
600	110304.60	
800	111178.80	
1000	111576.20	

RS

TF Len (bytes)	Throughput (Bps)	SP Len = 5 bytes
41	10497.56	
200	29316.75	
400	38129.13	
600	42371.25	
800	44863.38	
1000	46494.06	

TF Len (bytes)	Throughput (Bps)	SP Len = 194 bytes
41	22385.17	
200	62562.57	
400	81368.45	
600	90420.98	
800	95739.00	
1000	99218.88	

TF Len (bytes)	Throughput (Bps)	SP Len = 500 bytes
41	22787.50	
200	63693.75	
400	82850.00	
600	92075.00	
800	97481.25	
1000	101025.00	

TF Len (bytes)	Throughput (Bps)	SP Len = 2000 bytes
41	22750.00	
200	64000.00	
400	83350.00	
600	92700.00	
800	98250.00	
1000	101800.00	

TF Len (bytes)	Throughput (Bps)	SP Len = 20000 bytes
41	21646.67	
200	63046.36	
400	82000.00	
600	91250.00	
800	96500.00	
1000	100500.00	

TF Len (bytes)	Throughput (Bps)	SP Len = 60000 bytes
41	19661.11	
200	60300.00	
400	80105.96	
600	89086.09	
800	95682.12	
1000	98781.46	

Table 46. Selected Throughput Results Sorted By Transfer Frame Payload Length

No RS

SP Len (bytes)	Throughput (Bps)	TF Len = 41bytes
5	40531.69	
194	84816.80	
500	85131.25	
2000	87675.00	
20000	86126.67	
60000	85876.67	

SP Len (bytes)	Throughput (Bps)	TF Len = 200 bytes
5	50611.63	
194	108028.90	
500	109643.80	
2000	109675.00	
20000	108264.90	
60000	104420.00	

SP Len (bytes)	Throughput (Bps)	TF Len = 400 bytes
5	52225.88	
194	111457.90	
500	113456.30	
2000	113825.00	
20000	111750.00	
60000	109668.90	

SP Len (bytes)	Throughput (Bps)	TF Len = 600 bytes
5	52775.06	
194	112631.60	
500	114643.80	
2000	115225.00	
20000	113000.00	
60000	110304.60	

SP Len (bytes)	Throughput (Bps)	TF Len = 800 bytes
5	53058.13	
194	113237.80	
500	115318.80	
2000	115975.00	
20000	113750.00	
60000	111178.80	

SP Len (bytes)	Throughput (Bps)	TF Len =1000 bytes
5	53220.63	
194	113574.90	
500	115593.80	
2000	116425.00	
20000	113750.00	
60000	111576.20	

RS

SP Len (bytes)	Throughput (Bps)	TF Len = 41 bytes
5	10497.56	
194	22385.17	
500	22787.50	
2000	22750.00	
20000	21646.67	
60000	19661.11	

SP Len (bytes)	Throughput (Bps)	TF Len = 200 bytes
5	29316.75	
194	62562.57	
500	63693.75	
2000	64000.00	
20000	63046.36	
60000	60300.00	

SP Len (bytes)	Throughput (Bps)	TF Len = 400 bytes
5	38129.13	
194	81368.45	
500	82850.00	
2000	83350.00	
20000	82000.00	
60000	80105.96	

SP Len (bytes)	Throughput (Bps)	TF Len = 600 bytes
5	42371.25	
194	90420.98	
500	92075.00	
2000	92700.00	
20000	91250.00	
60000	89086.09	

SP Len (bytes)	Throughput (Bps)	TF Len =800 bytes
5	44863.38	
194	95739.00	
500	97481.25	
2000	98250.00	
20000	96500.00	
60000	95682.12	

SP Len (bytes)	Throughput (Bps)	TF Len = 1000 bytes
5	46494.06	
194	99218.88	
500	101025.00	
2000	101800.00	
20000	100500.00	
60000	98781.46	

Table 47. Selected Data Quality Results Sorted By Source Packet Payload Length

NO RS

TF Len (bytes)	Data Quality (%)	SP Len = 5 bytes
41	45.23	
200	43.77	
400	43.47	
600	43.36	
800	43.31	
1000	43.27	

TF Len (bytes)	Data Quality (%)	SP Len = 194 bytes
41	91.75	
200	93.42	
400	92.77	
600	92.53	
800	92.43	
1000	92.33	

TF Len (bytes)	Data Quality (%)	SP Len = 500 bytes
41	91.64	
200	94.18	
400	94.19	
600	94.19	
800	94.12	
1000	93.97	

TF Len (bytes)	Data Quality (%)	SP Len = 2000 bytes
41	91.33	
200	93.98	
400	94.34	
600	94.43	
800	94.50	
1000	94.52	

TF Len (bytes)	Data Quality (%)	SP Len = 20000 bytes
41	89.72	
200	92.70	
400	92.55	
600	92.62	
800	92.67	
1000	92.29	

TF Len (bytes)	Data Quality (%)	SP Len = 60000 bytes
41	88.81	
200	89.39	
400	90.85	
600	90.36	
800	90.55	
1000	90.52	

RS

TF Len (bytes)	Data Quality (%)	SP Len = 5 bytes
41	44.08	
200	43.88	
400	43.79	
600	43.74	
800	43.71	
1000	43.68	

TF Len (bytes)	Data Quality (%)	SP Len = 194 bytes
41	93.23	
200	93.64	
400	93.44	
600	93.33	
800	93.27	
1000	93.20	

TF Len (bytes)	Data Quality (%)	SP Len = 500 bytes
41	94.80	
200	94.97	
400	94.96	
600	95.05	
800	94.96	
1000	94.90	

TF Len (bytes)	Data Quality (%)	SP Len = 2000 bytes
41	94.59	
200	95.31	
400	95.42	
600	95.54	
800	95.57	
1000	95.52	

TF Len (bytes)	Data Quality (%)	SP Len = 20000 bytes
41	89.99	
200	93.85	
400	93.98	
600	94.07	
800	93.92	
1000	94.37	

TF Len (bytes)	Data Quality (%)	SP Len = 60000 bytes
41	81.73	
200	89.73	
400	91.72	
600	91.73	
800	93.04	
1000	92.62	

Table 48. Data Quality Results Sorted By Transfer Frame Payload Length (Part 1 of 2)

TF Len = 41 bytes

	No RS	RS
SP Len (bytes)	Data Quality (%)	Data Quality (%)
5	45.23	44.08
194	91.75	93.23
500	91.64	94.80
1000	91.43	94.80
2000	91.33	94.59
6000	90.62	93.44
20000	89.72	89.99
60000	88.81	81.73

TF Len = 200 bytes

	No RS	RS
SP Len (bytes)	Data Quality (%)	Data Quality (%)
5	43.77	43.88
194	93.42	93.64
500	94.18	94.97
1000	94.00	95.33
2000	93.98	95.31
6000	93.32	94.97
20000	92.70	93.85
60000	89.39	89.73

TFLen = 400 bytes

	No RS	RS
SP Len (bytes)	Data Quality (%)	Data Quality (%)
5	43.47	43.79
194	92.77	93.44
500	94.19	94.96
1000	94.48	95.43
2000	94.34	95.42
6000	93.91	95.11
20000	92.55	93.98
60000	90.85	91.72

TFLen = 600 bytes

	No RS	RS
SP Len (bytes)	Data Quality (%)	Data Quality (%)
5	43.36	43.74
194	92.53	93.33
500	94.19	95.05
1000	94.45	95.44
2000	94.43	95.54
6000	94.04	95.21
20000	92.62	94.07
60000	90.36	91.73

Table 49. Data Quality Results Sorted By Transfer Frame Payload Length (Part 2 of 2)

No RS

SP Len (bytes)	Data Quality (%)	TF Len = 800 bytes
5	43.31	
194	92.43	
500	94.12	
1000	94.45	
2000	94.50	
6000	94.01	
20000	92.67	
60000	90.55	

SP Len (bytes)	Data Quality (%)	TF Len = 1000 bytes
5	43.27	
194	92.33	
500	93.97	
1000	94.40	
2000	94.52	
6000	94.04	
20000	92.29	
60000	90.52	

RS

SP Len (bytes)	Data Quality (%)	TF Len = 800 bytes
5	43.71	
194	93.27	
500	94.96	
1000	95.43	
2000	95.57	
6000	95.40	
20000	93.92	
60000	93.04	

SP Len (bytes)	Data Quality (%)	TF Len = 1000 bytes
5	43.68	
194	93.20	
500	94.90	
1000	95.34	
2000	95.52	
6000	95.29	
20000	94.37	
60000	92.62	

APPENDIX J - Acronyms & Abbreviations

AFIT - Air Force Institute of Technology
ANOVA - Analysis of Variance
ARTM JPO - Advanced Range Telemetry, Joint Program Office
ATM - Asynchronous Transfer Mode
BEP - Bit Error Probability
BER - Bit Error Rate
bps - Bits Per Second
Bps - Bytes Per Second
CCSDS - Consultative Committee for Space Data Systems
DoD - Department of Defense
IRIG - Inter-Range Instrumentation Group
GPS - Global Positioning System
PCM - Pulse Code Modulation
QoS - Quality of Service
RCC - Range Commander's Council
RF - Radio Frequency
RS - Reed-Solomon encoding
Sec - Seconds
SP - Source Packet
TDMA - Time Division Multiple Access
TF - Transfer Frame
TM - Telemetry
TPS - Test Pilot School

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Vita

Captain BethAnn Trapp was born in October 1971 in Silver Spring, Maryland. She graduated from Meade Senior High School in Ft. Meade, Maryland in June 1989. She entered undergraduate studies at Purdue University in West Lafayette, Indiana where she graduated with a Bachelor of Science degree in Electrical Engineering in May 1993. She was commissioned through the Detachment 220 AFROTC at Purdue University where she was recognized as a Distinguished Graduate.

Her first assignment was at Goodfellow AFB as a student in USAF Intelligence School where she was recognized as a Distinguished Graduate. In November 1994, she was assigned to the 605th Air Intelligence Flight, Yokota AB, Japan where she served as Officer In Charge of Current Intelligence. In June 1996 she moved to 5th Air Force, Yokota AB, Japan where she served as Chief of Intelligence Systems. In November 1997 she was reassigned to the 426th Intelligence Squadron at Vogelweh Cantonmt, Germany. Here she served as a foreign computer and communications analyst. She was then reassigned in October 1998 to the 26th Intelligence Group where she served as the Group Executive Officer. In August 1999 she entered the Graduate Electrical Engineering program, Graduate School of Engineering and Management, Air Force Institute of Technology (AFIT) at Wright-Patterson AFB, Ohio. Capt Trapp also completed the USAF Test Pilot School in December 2001, earning the rating of Flight Test Engineer. Upon graduation from AFIT, she will be reassigned to the 418th Flight Test Squadron at Edwards AFB to work on the C-17 program.

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14. ABSTRACT

The DoD test range community has come to the realization that its telemetry abilities are obsolete. Efforts are therefore underway to improve telemetry systems at DoD test ranges. The overall objective of this project was to evaluate the practical use of the CCSDS packet telemetry protocol in DoD test ranges and determine the configuration that would maximize performance based on mission requirements. A secondary objective was to compare the CCSDS and ATM protocols in order to substantiate further exploration of using ATM in future DoD telemetry systems.

Modeling and simulation of the CCSDS protocol showed a correlation between three CCSDS parameters and the resulting throughput and data quality performance. Flight tests confirmed the correlation between the CCSDS parameters and the resulting protocol performance, and narrowed in on the CCSDS configurations that would maximize data throughput, data quality, or provide a combined "best of both worlds" solution. In general, flight test results matched those of the modeling and simulation work.

Data collected also indicated that performance of the ATM protocol is sufficiently close to that of CCSDS to warrant further investigation of using ATM on test ranges. ATM offers the military user straightforward interoperability with civilian systems/networks.

15. SUBJECT TERMS

CCSDS (Consultative Committee for Space Data Systems), Asynchronous Transfer Mode, telemetry, packets, protocol, Reed-Solomon code, packet protocols

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