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INTEGRATED SOURCE AND CHANNEL ENCODED DIGITAL COMMUNICATIONS SYSTEM DESIGN STUDY

FINAL REPORT

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I. INTRODUCTION

This report summarizes the studies of the digital communication system for the direct communication links from ground to Space Shuttle and the links involving the Tracking and Data Relay Satellite (TDRS). Three main tasks were performed: 1) Channel Encoding/Decoding Parameter Optimization for Forward and Reverse TDRS Links, 2) Integration of Command Encoding/Decoding and Channel Encoding/Decoding, and 3) Modulation-Coding Interface Study. Section II presents the general communication environment to provide the necessary background for the tasks and to provide an understanding of the implications of the results of the studies. A summary of the results of Task 1 is presented in Section III with further details in Reference 1. Task 2 is summarized in Section V with Reference 3 providing the detailed results of the study. Finally, Task 3 is summarized in Sections IV and VI, with further details in References 2 and 4. As a result of the studies of the Space Shuttle communication system, a number of additional studies that need to be performed are identified and presented in Section VII.

II. SPACE SHUTTLE COMMUNICATION ENVIRONMENT

The Tracking and Data Relay Satellite (TDRS) system is designed to provide tracking, data, telementry, command, and voice relay services to several classes of user satellites, including the space shuttle. This satellite system will provide increased communication coverage over the existing STDN (space flight tracking and data network). In addition, the use of the TDRS system will provide NASA with a potential reduction in network operating cost by deactivating several of the existing STDN ground stations. The system being proposed consists of two relay satellites located 130 degrees apart in longitude and a single ground station located within the continental United States. This arrangement will provide about 85 percent coverage for low-altitude (160 kilometer) spacecraft as opposed to the average coverage of about 27 percent provided by the existing STDN.

The advantages of the TDRS system are not without accompanying disadvantages in terms of the implementation of the communication equipment on the spacecraft. Typically, the links betweeen a low-altitude spacecraft and the STDN ground stations are very strong, even though the spacecraft employs low-power transmitters, high-noise receivers, and omnidirectional antennas. However, the path length of the link between a low-altitude manned spacecraft and the TDRS is significantly longer, and the TDRS has much less capability than the STDN ground station. Therefore, the communication links involving the spacecraft and the TDRS are much weaker than the direct links between the spacecraft and the ground stations. For these links involving the TDRS, it is extremely important to design an efficient communication system which minimizes the transmitting and receiving system losses.

A highly efficient S-band communication system is being studied for the communication links involving the spacecraft and the TDRS. An all-digital signal design is employed because it offers a number of advantages for transmission of voice, data, and commands over the more conventional analog techniques. First, digital speech with source coding such as variable-slope delta modulation is an efficient technique for voice transmission. Second, with digital speech, efficient time-division multiplexing of the speech, data, and commands is possible. Finally, forward error correction coding such as convolutional encoding with Viterbi decoding is possible to significantly reduce the power requirements and improve the link efficiency.

The variable-slope delta modulation is chosen for the source coding of the voice because of excellent performance at relatively low sampling rates, wide dynamic range, relative insensitivity to channel bit errors and design simplicity. The data rate for the digital voice channels is assumed to be 32 kbps. The voice quality at this data rate is particularly good for a bit error probability of less than 10^{-2}.

Two 32 kbps digital voice channels are time-division multiplexed prior to transmission with a 6.4 kbps encoded command channel and a 1.6 kbps synchronization channel resulting in a data rate of 72 kbps. Discretion was used in choosing the data rates of these channels to provide significant simplifications in both spaceborne and ground station equipment.

Convolutional encoding with 3-bit soft decision Viterbi decoding is selected for the all-digital system under consideration because of the very favorable tradeoff between performance gain and hardware complexity. A code rate of 1/3 and constraint length of K = 7 is used for transmission of voice, data, and commands.

The S-band transmission system described in the preceding paragraphs for the forward link is summarized in figure 2.1. The multiplexed data rate is 72 kbps, with the data rate out of the convolutional encoder equal to 216 kbps.

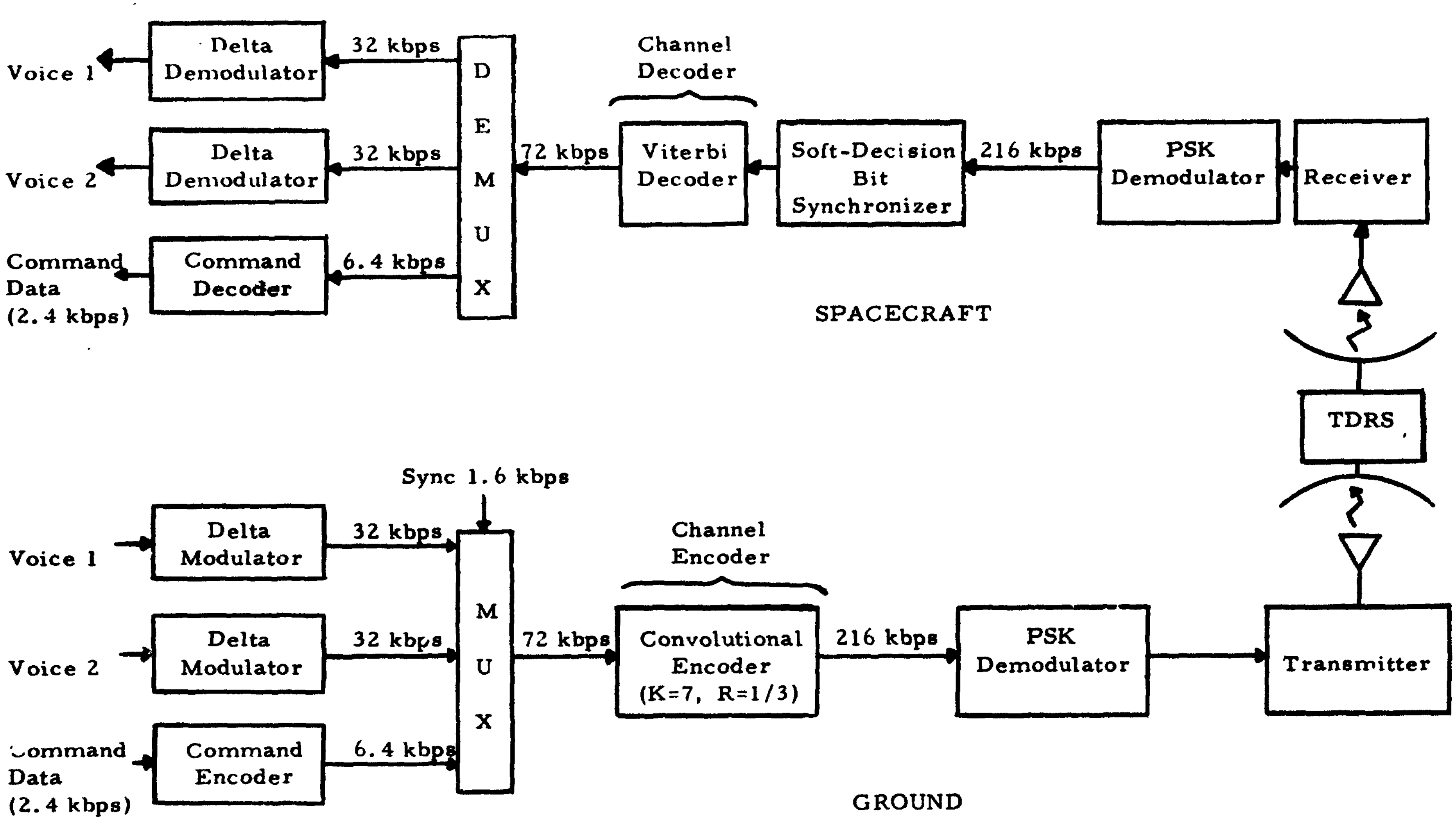

Figure 2.1. Forward Link Communication System Block Diagram

III. SUMMARY OF VITERBI DECODER PERFORMANCE AND COMPLEXITY

Viterbi decoding of a convolutional code is employed in the Space Shuttle digital communication system to increase the efficiency of the communication link. Reference 1 presents the performance, complexity, and availability of Viterbi decoder hardware.

Convolutional encoding with 3-bit soft-decision Viterbi decoding is selected for the all-digital system under consideration because of the very favorable tradeoff between performance gain and hardware complexity. A code rate of 1/3 and constraint length K=7 is selected to be used for transmission of voice, data, and commands.

The performance of the Viterbi decoder was predicted using analytical techniques. These analytical performance estimates are extremely accurate (i.e., within 0.1 dB at 10^{-4} probability of error per bit) and are also extremely simple to compute. Using these techniques, it was found that a bit energy per single-sided noise spectral density (E_b/N_0) of 3.2 dB is required to achieve a probability of error per bit of 10^{-4} with a Viterbi decoder for a code rate of 1/3 and constraint length K=7 convolutional code. This analytical result agrees with computer simulations.* A performance gain is achieved using the Viterbi decoder since 5.2 dB less E_b/N_0 is required with the Viterbi decoder than with uncoded PSK. Alternately, with a Viterbi decoder of

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*B. H. Batson, R. W. Moorehead, and S. Z. H. Taqui, "Simulation Results for the Viterbi Decoding Algorithm," NASA Technical Report R-396, Washington, D.C., November 1972.

equal complexity for a code rate 1/2 and constraint length K=7, it is found that E_b/N_0 = 3.6 dB is required to achieve a bit probability of error equal to 10^{-4}. These results also have been verified by computer simulations.* Hence, the Viterbi decoder for the rate 1/3 code provides an additional 0.4 dB performance gain over the rate 1/2 code. It has been found that this 0.4 dB is achievable since the additional degradation in the symbol synchronizer is negligible due to decreasing the rate from 1/2 to 1/3 (i.e., increasing the signaling rate from 144 kbps to 216 kbps). However, it should be noted that the analytical performance estimates indicate that, by increasing the complexity of the rate 1/2 Viterbi decoder by increasing the path memory length from 32 to 40, decreases the required E_b/N_0 by 0.1 dB. This decrease is not available for the rate 1/3 Viterbi decoder. Thus, the rate 1/3 Viterbi decoder provides only a 0.3 dB performance gain over the more complex rate 1/2 Viterbi decoder. However, this result should be verified with computer simulations.

Reference 1 presents the results of a survey of the available Viterbi decoder hardware. While it was found that there were no space-qualified or flight models of the Viterbi decoder, two companies (Linkabit and Radiation, Inc.) have operational Viterbi decoders for ground equipment. In addition, a number of companies have made paper designs and built breadboard versions. Predominantly, code rate 1/2 Viterbi decoders have been built, but all the companies surveyed agreed that a rate 1/3 Viterbi decoder represents no

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*J. A. Heller and I. M. Jacobs, "Viterbi Decoding for Satellite and Space Communication," IEEE Transactions on Communications Techniques, Vol. COM-19, No. 5, October 1971, pp. 835-848.

development differences than rate 1/2 and a similar complexity may be expected (i.e., 80-100 ICs and possibly less, depending on the logic development in the near future). Therefore, since a development is required for space-qualified flight equipment, there seems to be no disadvantage in selecting the rate 1/[illegible] Viterbi decoder for the Space Shuttle.

IV. SUMMARY OF SYMBOL SYNCHRONIZER STUDY FOR SHUTTLE COMMUNICATIONS

The Space Shuttle digital communication system was designed to have a large coding gain which results in a very small ratio of energy per symbol to single-sided noise spectral density (E_s/N_0) available for symbol synchronization. Yet, to achieve the expected coding gains, the symbol synchronizer must introduce negligible degradation.

Three fundamental types of symbol synchronizer loops have been analyzed in Reference 2. These loops are the sample function synchronizer, the early-late gate synchronizer, and the data transition tracking synchronizer. The synchronizer analysis concluded that the early-late gate slightly outperforms the other two synchronizers for the expected doppler of 55 kHz and doppler rate of 4.1 kHz per second at E_s/N_0 = -5 dB. However, the data transition tracking synchronizer performs nearly as well and is simpler to implement. It was also found that the degradation of a symbol synchronizer was not significantly greater for a rate 1/3 convolutional code than for a rate 1/2 code.

The loop bandwidth required for the early-late gate synchronizer to achieve negligible system performance degradation is 64 Hz while the other loops investigated need a bandwidth of 15 Hz for the same degradation. Thus, the early-late gate would acquire symbol synchronization faster than the other loops. But the acquisition analysis shows that none of the synchronizers with their optimized tracking loop bandwidths can acquire in a reasonable time for the conditions of E_s/N_0 = -5 dB and the expected doppler and doppler rate. It is shown, however, that acquisition is possible in 0.05 seconds for these conditions if a separate acquisition device is employed. Thus, either the acquisition must be performed by a separate device and handed over to the tracking loop or a wider loop bandwidth must be used during acquisition which is narrowed for tracking.

V. SUMMARY OF COMMAND CHANNEL CODING PERFORMANCE AND COMPLEXITY

A simply implemented command encoding/decoding scheme for space shuttle application is presented in Reference 3. Specifically, the coding scheme was designed to be used on weak (data relay) links employing Viterbi decoding for error correction and possibly COMSEC equipment for security. Also, the command coding can be used alone on strong (direct) links with possibly COMSEC equipment for security. The Viterbi decoding and COMSEC equipment, while providing improved bit error rate and security, respectively, result in a deleterious burst error environment for the command coding scheme. Reference 3 describes in detail the environment, a simple command decoder implementation, and the performance of the command coding scheme.

The burst error statistics of the ($K = 7$, $R = 1/3$) Viterbi decoder and the error extension phenomenon of COMSEC equipment were investigated. A command channel encoder and decoder were designed to be compatible with the Shuttle multiplexing format and the presence of the Viterbi decoder and the COMSEC equipment. The implementation of the command encoder and decoder was very simple, consisting of a 50 stage feedback shift register. The resulting decoder more than met the specification for the probability of acceptance of an incorrect command to be less than 10^{-18}. Also, the specification of a probability of command rejection of 10^{-2} is met with $E_b/N_0 = 3.4$ dB at the Viterbi decoder when no COMSEC unit is used and with $E_b/N_0 = 4.2$ dB when the COMSEC unit is used. When the COMSEC unit is used alone, a probability of error equal to 10^{-5} or less is required at the input to the COMSEC unit in order to meet the 10^{-2} probability of command rejection requirement.

VI. SUMMARY OF ORBITER TO PAYLOAD COMMAND PERFORMANCE WITH A SPLIT PHASE SYMBOL SYNCHRONIZER

A command link is being designed to operate between the Space Shuttle Orbiter and a payload. The primary concern is the effect that a symbol synchronizer slip has on this link. In Reference 4, the command link is discussed along with the format of the command word. The symbol synchronizer in this link was analyzed and shown to have an extremely small probability of slipping a cycle. However, to maintain the required probability of acceptance of an erroneous command, a strategy for detecting a cycle slip and disregarding the previous command was presented. The results of the analysis demonstrated that, with the expected symbol error rate of this link and a typical loop bandwidth, the loop SNR would be very large (≈ 48.5 dB) so that the probability of a cycle slip is incalculably small. A strategy of detecting a cycle slip using the PN sync word was given. It was shown that the probability of falsely declaring a slip (thus falsely rejecting a command) could be made to be negligible ($< 10^{-36}$) for the expected symbol error rate of $p = 10^{-4}$. Also, the probability of missing a slip if it occurs is shown to be approximately 8×10^{-21}. These values show acceptable performance and were found to occur when the number of acceptable errors is $K = 10$. Thus, the strategy of using the sync word to detect a slipped cycle was shown to yield excellent performance.

VII. AREAS FOR FURTHER STUDY

During the course of the contract, a number of problem areas were identified that require further study.

7.1 SYSTEM MODELING AND PARAMETER OPTIMIZATION

It is very important to accurately predict the performance of the communication system since the communication link margins are extremely small. Therefore, further investigations of the individual components of the system are required to develop a mathematical model capable of accurately predicting nominal and worst-case system behavior. Considering the trade-offs between performance, complexity, and availability of hardware, the critical system parameters need to be further identified and optimized.

7.2 SYSTEM ACQUISITION CHARACTERISTICS

The acquisition characteristics of the digital transmission system for communications either directly from ground to the Space Shuttle or via TDRS need to be determined. Carrier, symbol synchronization, Viterbi decoder branch synchronization, and multiplexer frame synchronization acquisition need to be studied, and a total system acquisition time should be predicted as a function of the received signal-to-noise ratio. Effects such as antenna switching on system acquisition should be investigated. A basic set of acquisition techniques and procedures needs to be developed for both direct and TDRS links.

7.3 MODULATION-CODING INTERFACE CHARACTERISTICS

Sources of performance degradation on the Viterbi decoder due to the PSK demodulation and bit synchronization need to be identified. An analysis is needed to determine the design parameters of the Costas (or squaring) loop for PSK demodulation including the bandwidths of the low pass filters when split-phase (Manchester coding) is employed and the characteristic of the limiter (if needed) preceding the Costas loop. Also, the types of AGC need to be compared and the effects that the AGC has on the system performance need to be investigated. The interface between the receiver PSK demodulator and the digital signal processor needs to be carefully analyzed to minimize the signal processor performance degradation.

7.4 SECURITY INTERFACING FOR PAYLOAD AND GROUND COMMUNICATION LINKS

An analysis and evaluation is needed of the system impact of interfacing communications security equipment with the remaining orbiter communication subsystem equipment for periodic use on payload and ground communications links. Attention should be given to the impacts, including implementation considerations, of this processing on command, control, data, and voice channels.

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