LOW - RATE COMMUNICATIONS UTILIZING DIGITAL CODING AND MODULATION

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SUMMARY

A highly efficient all-digital communications signal design employing convolutional coding and optimum (PSK) modulation is described for two-way transmission of voice and low-rate (several kbps) data between the space shuttle and ground. Variable-slope delta modulation is selected for analog/digital conversion of the voice signal. A convolutional decoder based on the Viterbi decoding algorithm is selected for use at the receiving terminal. Performance predictions (both theoretical and experimental) are presented for transmission via the Intelsat IV relay satellite system, with application of state-of-the-art technology to the space shuttle RF system. Hardware estimates are provided for an actual flight-qualified communications system employing the coded digital signal design.

INTRODUCTION

It will be possible to maintain almost continuous communications between the space shuttle and ground by utilizing a system of two or more relay satellites and perhaps no more than a single ground station. However, launch vehicle constraints will limit the allowable relay satellite size and weight and, therefore, its antenna sizes and transmitter powers. The capabilities of existing (and currently conceived) relay satellites are such that the links between the space shuttle and satellite will be extremely power-limited. Consequently, it will be important to utilize highly efficient communications signal designs which minimize the required shuttle transmitter power and transmit/receive antenna gains, and which minimize the requirement for very low noise receivers on the shuttle.

All-digital communications signal designs have appeared increasingly attractive in recent years for applications in which maximum link efficiency is an important design goal. One favorable characteristic of all-digital designs is that error control encoding/decoding can be applied to achieve significant improvements in overall link performance. The introduction of coding into a digital link allows, for a fixed transmitted (or received) power level and for an allowable bit error probability, transfer of more information per unit time. Alternately, for a fixed information rate, the introduction of coding can provide a reduction in the transmitted (or received) power level required to maintain a specified error probability. The exact increase in information rate which can be achieved, or the amount of coding gain (allowable reduction in power level) which is realizable depends on the particular class of encoding/decoding technique employed and on various encoder and decoder parameters which must be selected by the communications system design engineer.

INTRODUCTION

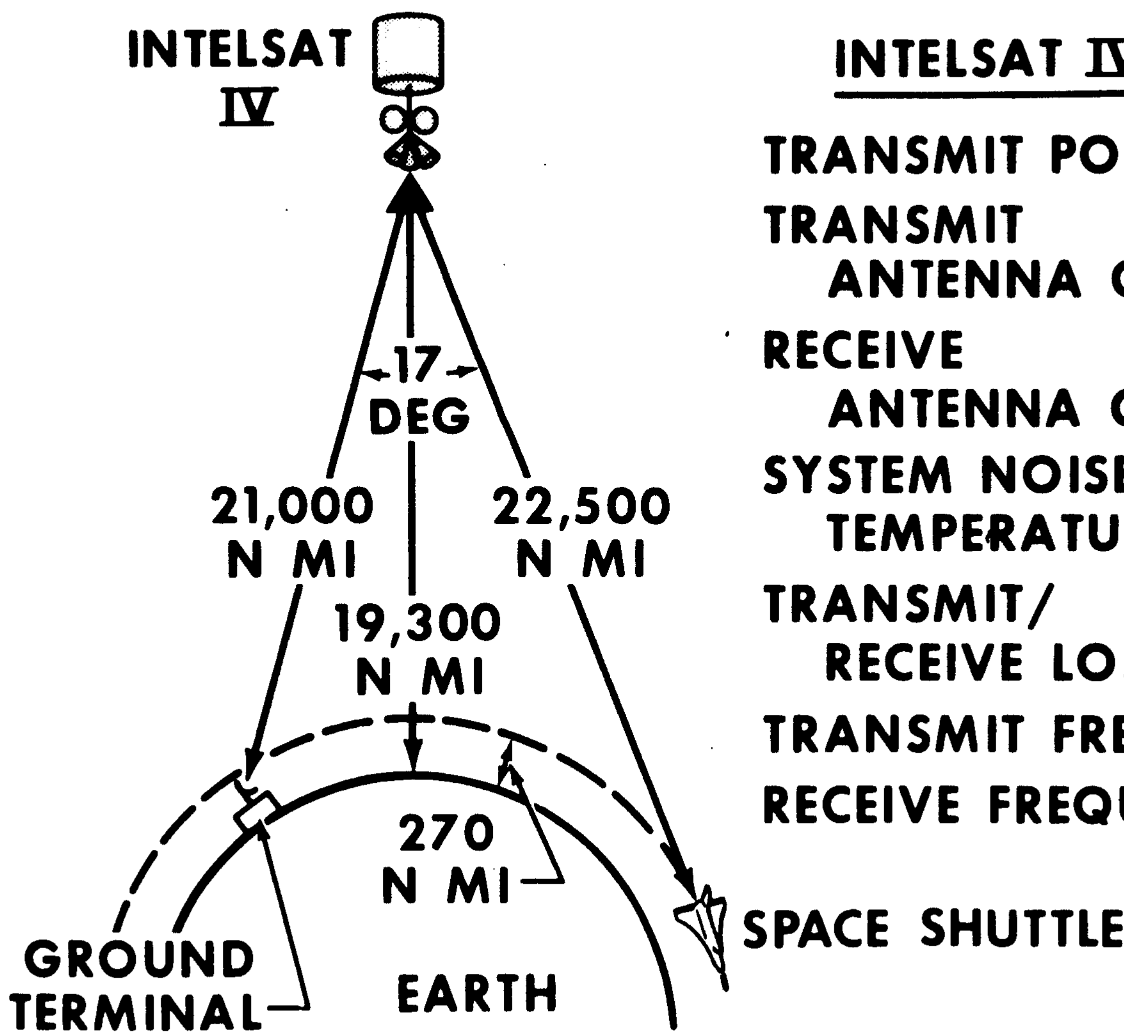
- INCREASED COMMUNICATIONS COVERAGE POSSIBLE USING SYSTEM OF RELAY SATELLITES
- LIMITED CAPABILITIES OF RELAY SATELLITES RESULT IN POWER-LIMITED LINKS
- CURRENT TECHNOLOGY IN SIGNAL PROCESSING TECHNIQUES CAN BE APPLIED TO IMPROVE LINK EFFICIENCIES
- EXAMPLE: TWO-WAY TRANSMISSION OF VOICE AND DATA BETWEEN SHUTTLE AND GROUND VIA INTELSAT IV
  - ANALOG (DUAL-SUBCARRIER) SYSTEM
  - ALL-DIGITAL SYSTEM

SHUTTLE COMMUNICATIONS VIA INTELSAT IV

Consideration will be given to two-way transmission of a single voice channel and a low-rate data channel between the space shuttle and an earth-based terminal, with relay through the Intelsat IV series of communications relay satellites. Intelsat IV is assumed as an example because it is already in existence and thus potentially represents a minimum-cost relay satellite system for manned space flight use. Also, because Intelsat IV is a very low-capability relay device for such applications, the resulting constraints on the shuttle communications system are more severe and point out more emphatically the need for application of the latest technological advances in RF equipment and in signal processing techniques.

The Intelsat IV transmit and receive antenna gains (16.5 dB and 16.7 dB, respectively) are relatively low at the C-band operating frequencies (4 GHz and 6 GHz). It is primarily because of these relatively low antenna gains that Intelsat IV is a low-capability relay device for applications typical of manned space flight.

SHUTTLE COMMUNICATIONS VIA INTELSAT IV



INTELSAT IV PARAMETERS

TRANSMIT POWER	6.3 WATTS
TRANSMIT ANTENNA GAIN	16.5 dB
RECEIVE ANTENNA GAIN	16.7 dB
SYSTEM NOISE TEMPERATURE	1160° K
TRANSMIT/RECEIVE LOSSES	2 dB
TRANSMIT FREQUENCY	4 GHz
RECEIVE FREQUENCY	6 GHz

PROJECT SHUTTLE RF CAPABILITIES

Should it be necessary to communicate between the space shuttle and ground via the Intelsat IV series of relay satellites, a directional antenna will be required on the shuttle. Minimization of the physical dimensions of such an antenna becomes a problem of major importance. It is, therefore, desirable to incorporate a high-power transmitter and a low-noise receiver at the shuttle terminal. Fortunately, technological advances are presently being made by NASA in both of these areas.

A high-efficiency C-band power amplifier now under development by the Langley Research Center will provide a 100-watt transmitter capability for the space shuttle. This power amplifier will provide a gain of more than 33 dB and will have an efficiency of nearly 50%. Development of this device is scheduled for completion by the fall of 1971, and the production of a flight-qualified version could be completed in 1972.

A wideband (100 MHz) low-noise (1.5-dB noise figure) C-band parametric amplifier now under development by the Goddard Space Flight Center is also expected to be available for the space shuttle program. Development of this device is scheduled to be completed by early 1972, and it is anticipated that flight-qualified hardware could be available later in 1972.

PROJECTED SHUTTLE RF CAPABILITIES

C-BAND POWER AMPLIFIER DEVELOPMENT - LANGLEY RESEARCH CENTER

POWER OUTPUT	100 WATTS
EFFICIENCY	45 PERCENT - 50 PERCENT
GAIN	>33 dB
WEIGHT	<20 POUNDS
SIZE	4 IN. x 7 IN. x 12 IN.
AVAILABILITY	1972

C-BAND PARAMETRIC AMPLIFIER DEVELOPMENT - GODDARD SPACE FLIGHT CENTER

NOISE FIGURE	1.5 dB
GAIN	17 dB
BANDWIDTH	100 MHz
WEIGHT	7 OUNCES
SIZE	3.5 IN. x 3.5 IN. x 0.5 IN.
AVAILABILITY	1972

SHUTTLE ANTENNA REQUIREMENTS FOR ANALOG TRANSMISSION SYSTEM (INTELSAT IV RELAY)

The information to be transmitted between the space shuttle and ground via Intelsat IV will be assumed to consist of a single voice channel and a 19.2-kbps data channel. In order to meaningfully assess the value of a coded digital transmission system, performance predictions will first be presented for a conventional Apollo-type (dual subcarrier) analog transmission system with optimized modulation parameters. The voice signal is assumed to frequency modulate one subcarrier, while the data signal phase modulates the second subcarrier, and a linear combination of the two modulated subcarriers phase modulates the main carrier. The performance criteria for the two channels are assumed to be the same as for the Apollo Program, i.e., 90% word intelligibility (corresponding to a 14-dB output signal-to-noise ratio) for the voice channel and 10^{-4} bit error probability for the data channel. The system parameters assumed for the shuttle are based on incorporation of the new C-band RF technology (high-power transmitters and low-noise receivers) considered earlier.

For the analog transmission system considered, the shuttle antenna diameter required to provide a 3-dB performance margin in each information channel is 4.5 feet for the downlink and 6.3 feet for the uplink. In order to provide the required two-way communications capability, then, the required shuttle antenna diameter is 6.3 feet.

SHUTTLE ANTENNA REQUIREMENT FOR ANALOG TRANSMISSION SYSTEM

INTELSAT IV RELAY

- INFORMATION CHANNELS
  - 1 FM VOICE CHANNEL
  - 1 DATA CHANNEL (19.2 KBPS)
- PERFORMANCE CRITERIA
  - 90-PERCENT WORD INTELLIGIBLITY
  - 10^{-4} BIT ERROR PROBABILITY
- ASSUMED SHUTTLE PARAMETERS
  - TRANSMIT POWER ———— 100 WATTS
  - TRANSMIT LOSSES ———— 2 dB
  - SYSTEM TEMPERATURE ———— 180° K
  - RECEIVE LOSSES ———— 1 dB
- REQUIRED ANTENNA DIAMETERS FOR 3-dB PERFORMANCE MARGINS
  - DOWNLINK ———— 4.5 FT
  - UPLINK ———— 6.3 FT

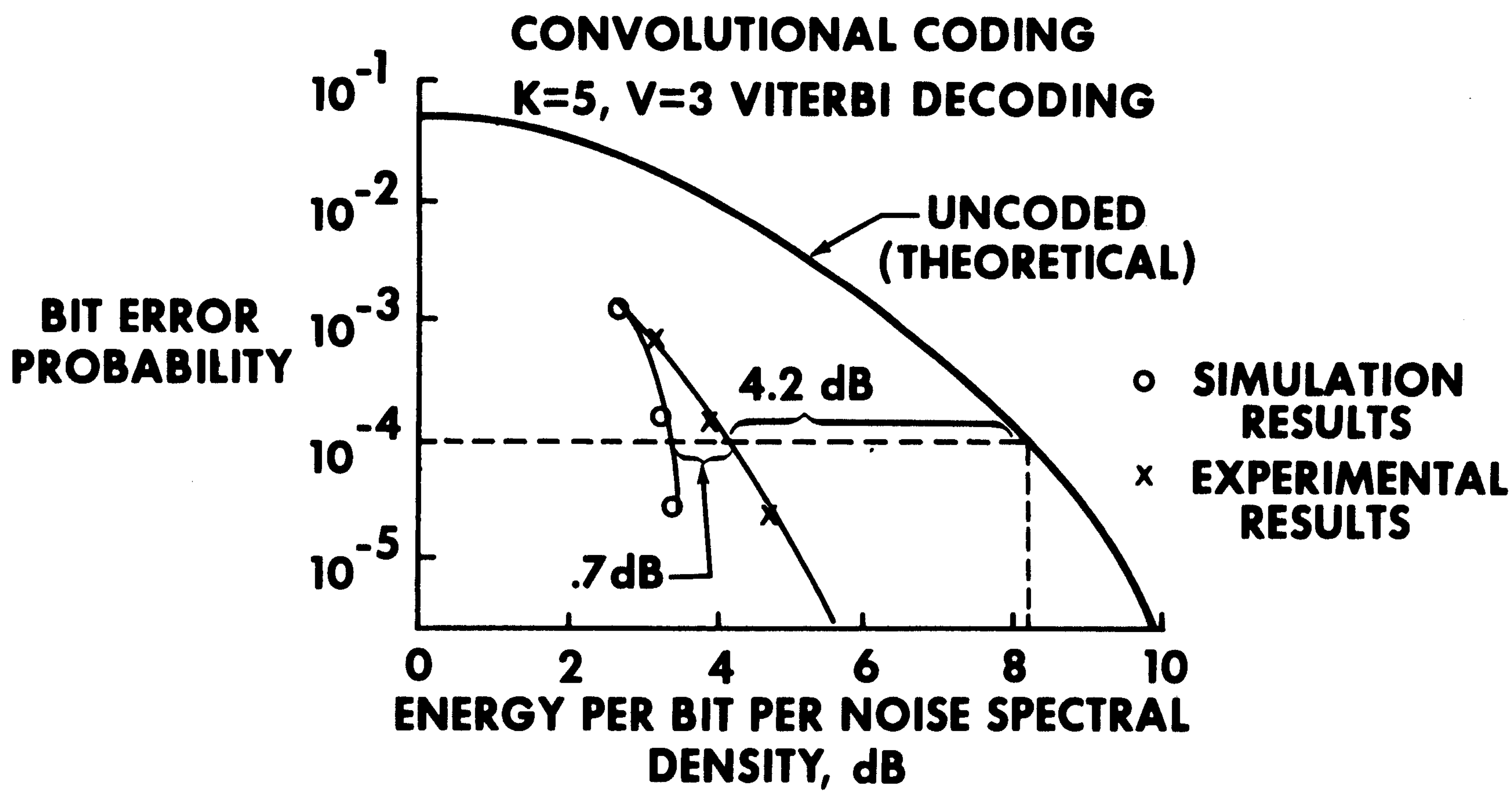
PERFORMANCE OF DIGITAL SYSTEMS UTILIZING ERROR CONTROL CODING

After reception and demodulation of a digital communications signal, it is necessary to decide which digital level was actually transmitted over each signalling interval. Because of the presence of noise, there is always a finite probability of error associated with these decisions. The probability of error is directly related to the amount of signal energy (E_b) contained in each bit at the input to the bit detector, and to the noise spectral density (N_o) at the receiver.

Several error correction encoding and decoding techniques are available for incorporation into a digital transmission system. As previously noted, the amount of coding gain which is realizable depends on the particular combination of encoding and decoding techniques which is employed. A characteristic common to all such techniques, however, is that redundancy is added on a controlled basis to the transmitted signal. That is, the number of bits transmitted per second over the channel is increased. Therefore, for fixed power levels, the introduction of coding results in a decrease in the available energy per bit at the bit detector input. The bit error probability at the bit detector output is thus greater with coding than with no coding. By applying a clever encoding/decoding scheme which makes efficient use of the controlled redundancy present in the encoded data, it is possible to reconstruct the original information signal with a lower bit error probability than before the introduction of coding.

Several recent studies have indicated that convolutional encoding, used in conjunction with Viterbi algorithm decoding, provides a good trade-off between performance gain and hardware complexity. Computer simulations performed at MSC predicted that a coding gain of about 4.9 dB should be achievable at an information bit error probability of 10^{-4}, for Viterbi decoding of a convolutional code with a constraint length (K) of 5 and a rate (1/V) of 1/3. The parameter K is the length of the shift register which is used to generate the convolutional code, while V is the number of channel bits transmitted for each information bit. A $K = 5$, $V = 3$ encoder and a Viterbi decoder were designed, fabricated, and tested in 1970; and the experimental coding gain provided by these devices is within 0.7 dB of these predictions. (0.3 dB of this variation from predicted performance was due to non-ideal operation of the bit detector.)

PERFORMANCE OF DIGITAL SYSTEMS UTILIZING ERROR CONTROL CODING



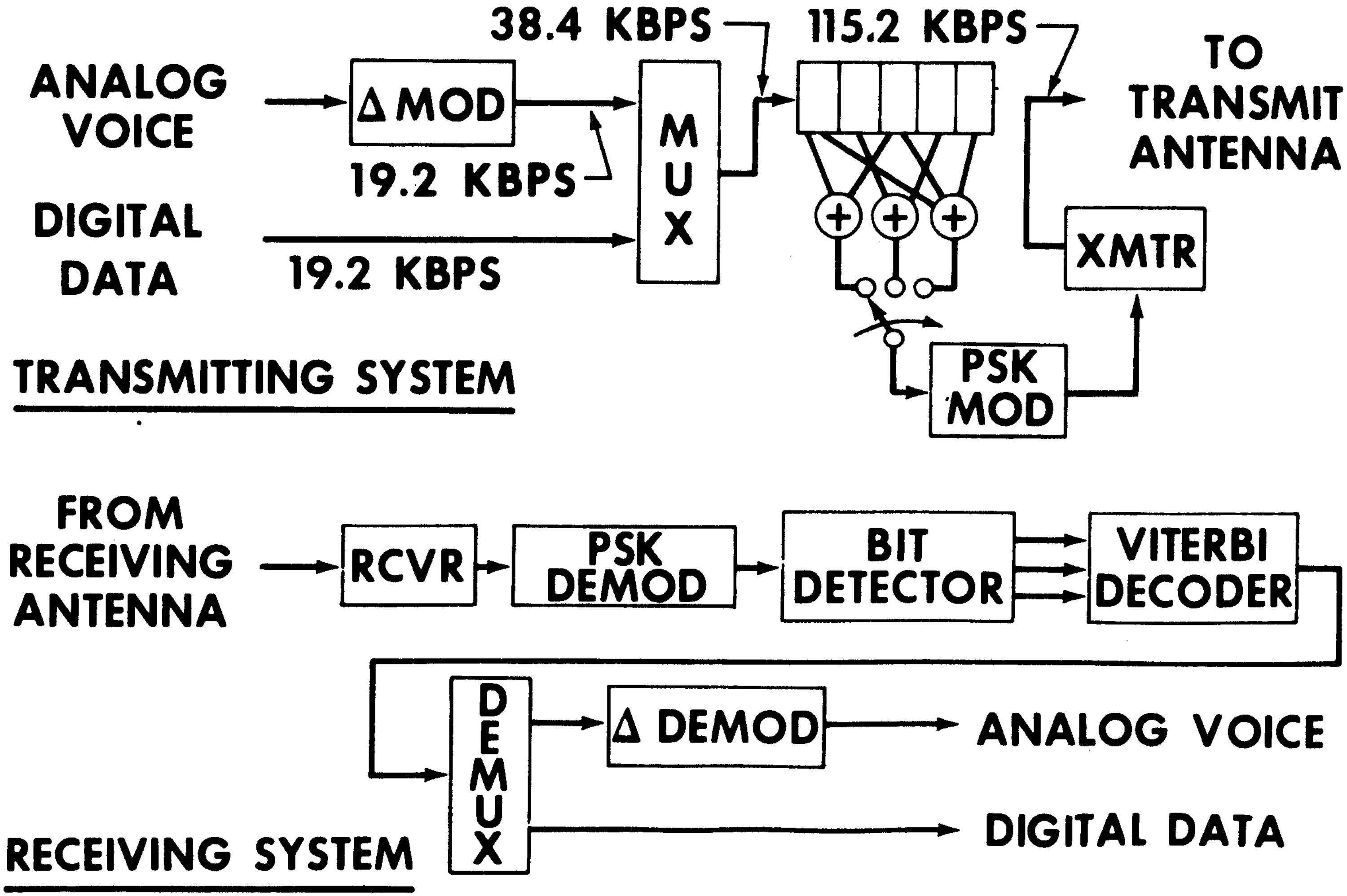
CODED DIGITAL TRANSMISSION OF VOICE AND DATA

The performance of an all-digital system for transmission of a voice channel and a 19.2-kbps data channel will now be contrasted with that of the Apollo-type analog transmission system considered earlier. Variable-slope delta modulation is chosen as the analog-to-digital conversion technique for the voice signal. The required sampling rate for delta modulation is higher than for PCM, but only one bit is required to represent each sample. For some classes of information signals (such as voice), the bit transmission rate required for a given measure of channel performance (such as 90% word intelligibility) is significantly lower for delta modulation. Additionally, tests at MSC indicate that delta modulation is much less sensitive to bit errors than PCM. Both of these factors (lower transmit bit rates and higher allowable error rates) allow reductions in transmit power levels for delta modulation systems. The voice channel transmit bit rate assumed for this example is 19.2-kbps.

The delta-modulated voice signal and the 19.2-kbps data signal, after being time-multiplexed are encoded by a rate 1/3 convolutional encoder. The channel bit rate at the encoder output is, therefore, 19.2 x 2 x 3 = 115.2 kbps. The coded bit stream is used to phase-shift-key (PSK) a carrier, and this PSK signal is power amplified and transmitted over the relay link.

After reception and demodulation of the digital signal, the noisy channel bits are input to an optimum (integrate-and-dump) bit detector. Rather than utilize "hard" bit decisions which indicate merely that the integrator contents were positive or negative at the end of a bit period, use is made of "soft" bit decisions which indicate both the sign and magnitude of the integrator contents. Soft decisions are implemented by quantizing the bit detector output voltages into three-bit words. These three-bit words, which represent estimates of the channel bits, are input to the decoder for error correction. After decoding, the delta-modulated voice and data are demultiplexed and converted to forms suitable for the final users.

CODED DIGITAL TRANSMISSION OF VOICE AND DATA



SHUTTLE ANTENNA REQUIREMENT FOR CODED DIGITAL TRANSMISSION SYSTEM (INTELSAT IV RELAY)

The parameters assumed for the shuttle are again based on incorporation of the expected C-band technological advances in high-power transmitters and low-noise receivers. The performance criterion for the digital transmission system is a 10^{-4} bit error probability at the output of the Viterbi decoder. This error probability exactly satisfies the performance criterion for the data channel and, according to tests performed at MSC, more than satisfies the 90% word intelligibility requirement for the voice channel.

The coded digital transmission system provides a 9.2-dB improvement in link performance over the Apollo-type analog transmission system considered. This improvement can be realized as a decrease in the required shuttle antenna size. For the digital system, the shuttle antenna diameter required to provide a 3-dB performance margin is 1.5 feet for the downlink and 2.2 feet for the uplink. The required two-way communications can, therefore, be maintained with a 2.2-foot shuttle antenna.

SHUTTLE ANTENNA REQUIREMENTS FOR CODED DIGITAL TRANSMISSION SYSTEM

INTELSAT IV RELAY

- INFORMATION CHANNELS
  - 1 DELTA MODULATED VOICE CHANNEL (19.2 KBPS)
  - 1 DATA CHANNEL (19.2 KBPS)
- PERFORMANCE CRITERIA
  - 10^{-4} OUTPUT INFORMATION BIT ERROR PROBABILITY
- ASSUMED SHUTTLE PARAMETERS
  - TRANSMIT POWER ———— 100 WATTS
  - TRANSMIT LOSSES ———— 2 dB
  - SYSTEM TEMPERATURE ———— 180° K
  - RECEIVE LOSSES ———— 1 dB
- REQUIRED ANTENNA DIAMETERS FOR 3-dB PERFORMANCE MARGIN
  - DOWNLINK ———— 1.5 FT
  - UPLINK ———— 2.2FT

FLIGHT HARDWARE ESTIMATES FOR CODED DIGITAL TRANSMISSION SYSTEM

Implementation of the digital transmission techniques considered earlier is entirely feasible at this time. Delta modulators and demodulators have been in field use by the military for several years, and various types of coding and decoding have been utilized in the unmanned deep-space programs. Breadboard versions of the delta modulator and demodulator and the convolutional encoder and Viterbi decoder have been fabricated and tested in MSC laboratories. Additionally, Viterbi decoders have recently been fabricated and tested independently by several industrial organizations. The present technology in digital logic is such that all of these devices could be available as flight-qualified hardware in 1972. The estimated power requirements, weights, and sizes of the flight hardware make these digital transmission techniques appear to be compatible with manned space flight applications. The hardware estimates are based on utilization of medium-scale integration. Large-scale integration could be applied to further reduce size and weight, but with a probable increase in cost.

FLIGHT HARDWARE ESTIMATES FOR CODED DIGITAL TRANSMISSION SYSTEM

DEVICE	COMPLEXITY, IC'S*	POWER REQMT, WATTS	WEIGHT, OZ	VOLUME, CU IN.	AVAILABILITY
VARIABLE-SLOPE DELTA MODULATOR	40	6	5	12	1972
VARIABLE-SLOPE DELTA DEMODULATOR	40	6	5	12	1972
CONVOLUTIONAL ENCODER	10	1.5	2	3	1972
VITERBI DECODER	60-65	9	8-10	40	1972

* Integrated Circuits

CONCLUSIONS

The digital transmission techniques which have been considered represent state-of-the-art technology in communications signal processing. These techniques, when incorporated into flight systems, provide a significant improvement in overall link efficiency. If state-of-the-art RF technology (high-power transmitters and low-noise receivers) is applied to the space shuttle communications system, then this improvement in efficiency is realizable as a decrease in the required shuttle antenna size. A smaller shuttle antenna is desirable because of the reduced penalty in weight and because of the reduced physical and mechanical penalties associated with storing, deploying, and positioning a smaller antenna. In addition, at a given frequency, beamwidth varies inversely with antenna diameter. The larger beamwidths associated with smaller antennas are desirable because the requirements on tracking accuracy can be relaxed.

It should be noted that, for the case of transmission of one voice channel and one low-rate data channel via the Intelsat IV relay satellite system, not even application of the latest technology in RF equipment and signal processing techniques can remove the requirement for a tracking antenna on the shuttle. In fact, if the communications requirement could be reduced to only a single voice channel (no data), a tracking antenna would still be required. If it is desired to operate without a tracking antenna on the shuttle, then it will be necessary to utilize a relay satellite system other than Intelsat IV.

CONCLUDING REMARKS

- DIGITAL TRANSMISSION TECHNIQUES WITHIN EXISTING TECHNOLOGY
- REAL AND SIGNIFICANT IMPROVEMENTS IN LINK EFFICIENCY ARE POSSIBLE
- IMPROVED LINK EFFICIENCY CAN DECREASE SIZE OF SHUTTLE TRACKING ANTENNA (OR INCREASE DATA RATE CAPABILITY)
- TRACKING ANTENNA ALWAYS REQUIRED IF INTELSAT IV IS USED