COMPRESSED TELEVISION TRANSMISSION: A MARKET SURVEY

October 1981

(NASA-CR-168614) COMPRESSED TELEVISION TRANSMISSION: A MARKET SURVEY (SRI International Corp., Menlo Park, Calif.) 58 p HC A04/MF A01 CSCL 17B

N82-19410

Unclas

G3/32 09258

Prepared for

National Aeronautics and
Space Administration
Technology Transfer Division
Code ETT6
Washington, D C 20546

Attention R L Gilbert

Contract NAS2-10143

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
US DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

SRI International
333 Ravenswood Avenue
Menlo Park, California 94025
(415) 326-6200
TWX 910-373-2046
Telex 334 486

SRI International

COMPRESSED TELEVISION TRANSMISSION: A MARKET SURVEY

October 1981

Prepared by

Ruth M Lizak
Laird Q Cagan

Prepared for

National Aeronautics and
Space Administration
Technology Transfer Division
Code ETT6
Washington, D C 20546

Attention R L Gilbert

Contract NAS2-10143

SRI Project 8134

SRI International®

NOTICE

THIS DOCUMENT HAS BEEN REPRODUCED FROM THE BEST COPY FURNISHED US BY THE SPONSORING AGENCY. ALTHOUGH IT IS RECOGNIZED THAT CERTAIN PORTIONS ARE ILLEGIBLE, IT IS BEING RELEASED IN THE INTEREST OF MAKING AVAILABLE AS MUCH INFORMATION AS POSSIBLE.

CONTENTS

LIST OF ILLUSTRATIONS iii

LIST OF TABLES. iv

PREFACE v

I INTRODUCTION. 1

II CURRENT AND PROPOSED TRAFFIC SURVEILLANCE SYSTEMS AND RELATED TECHNOLOGIES UNDER DEVELOPMENT. 3

Maryland Department of Transportation 3
California Department of Transportation 3
Golden Gate Bridge Highway and Transportation District. . 5
Michigan Department of Transportation 5
Ontario Ministry of Transportation. 5
Related Technologies Under Development 7

III NASA'S COMPRESSED TELEVISION TRANSMISSION 11

IV CTT POTENTIAL MARKET. 15

Teleconferencing. 15
Remote Medical Diagnosis. 16
Patient Monitoring. 16
Education 17
Defense 18
Traffic Management and Control. 18
Emergency Traffic Management. 18

V POTENTIAL MANUFACTURERS 20

VI CONCLUSIONS 22

REFERENCES. 24

Appendixes

A U.S. PATENT DESCRIPTION A-1

B ABSTRACTS B-1

C BLOCK ADAPTIVE RATE CONTROLLED IMAGE DATA COMPRESSION C-1

ILLUSTRATIONS

1 Relationship Between Highway Demand, Capacity, and Congestion 1

2 Compressed TV Transmission System Components 11

3 Frame Rate Versus Quality Trade-Off 12

4 Frame Rate Versus Quality of CTT 13

5 Comparison of CTT with Slow Scan Television Transmission 14

TABLES

1 Components of the Detroit Traffic Surveillance System . . . 6

2 Comparison of Belden and HDC Fiber Optics 9

3 Traffic Management Systems in Use and Interest in CTT in Selected State Highway Departments. 19

PREFACE

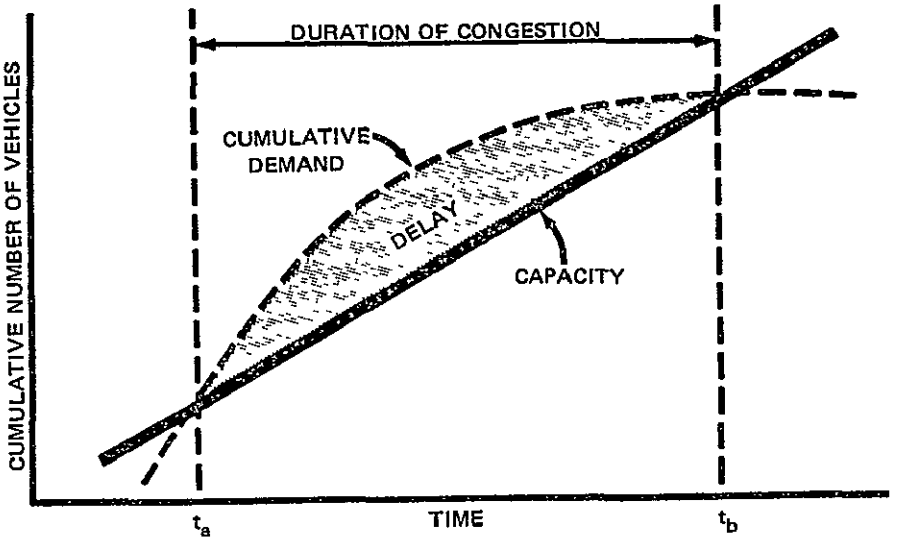
The NASA Technology Applications Team at SRI has been active in the NASA Technology Transfer Program for several years. The objectives of the program are to transfer aerospace technology to the solution of important technological problems in public transportation, to implement and continuously refine appropriate methods of ensuring successful transfers, and to provide visibility for program activities.

This analysis of the market for compressed television transmission technology was conducted as part of the SRI Team's highway effort. Mrs. Ruth Lizak is responsible for all program activities that relate to state and local highway problems.

I INTRODUCTION

Traffic flow enhancement has been an objective of highway engineers for many years and the reason for most highway construction. As highway traffic increased, roadways were widened or new highways were built. Today, however, these methods of traffic flow enhancement may not be possible due to limited financial resources for transportation investments, the increased costs of highway construction, the unavailability of land, and public concern about air quality.

Traffic delays caused by random events are referred to as temporary hazards or incidents. The effect of these incidents usually is the blocking of a lane or lanes on a highway, thereby creating a traffic bottleneck. The magnitude of this problem can be seen in Figure 1. The number of vehicles that accumulate upstream of the bottleneck depends on the duration of each congestion.



When traffic demand exceeds the service rate of a section of freeway, a bottleneck is formed, and vehicles will accumulate upstream of the bottleneck. The amount of delay is represented by the shaded area.

SOURCE: Transportation Research Board, "Freeway Traffic Management," September 1979

FIGURE 1 RELATIONSHIP BETWEEN DEMAND, CAPACITY, AND CONGESTION

*All references are listed at the end of the report.

The highway researcher has responded to this need for alternative means of alleviating highway traffic congestion by developing traffic surveillance and control systems. To date, these systems have relied primarily on two basic elements: (1) entrance ramp metering that regulates the rate of traffic flow onto the highway, and (2) incident detection and management that eliminates the lengthy traffic stoppage or near stoppage by rapidly detecting and removing the cause (e.g., the disabled vehicle, spilled load, or traffic accident).

Traffic surveillance and control systems were first tested about 20 years ago. The first systems relied heavily on loop detectors that consist of permanent magnets and imbedded coils. (A set of magnets is arranged such that a unique pattern of voltage is induced in a coil within the roadway. Passage of a vehicle interrupts the flow of current.) Advantages of such systems included simplicity and passivity; their primary disadvantage was the inability to transmit specific information about the cause of the congestion.

Later systems added television cameras and broadband coaxial cables to verify loop-detected problems and identify their causes. However, the cost for coaxial cable was, and still is, high. Telephone lines were considered for low-cost communication linkage, but the requisite compressed television images lacked clarity. Compression of images is necessary for telephone lines due to the small bandwidth of the lines.

Most recently, the Maryland Department of Transportation (DOT) began plans for a television-based traffic surveillance and control system for the Baltimore Beltway. Television imagery will be transmitted over telephone lines. The imagery would be compressed, however, with NASA-developed technology to ensure clarity. NASA-developed error protection would ensure reliability. Highly sophisticated compressed television transmission (CTT) is positionally constructed. If the image is out of synchronization, it loses its place, and thus it needs error protection (e.g., NASA's powerful channel coding techniques developed for the Jupiter mission).

This report describes NASA's CTT technology and considers its potential market; a market that encompasses teleconferencing, remote medical diagnosis, patient monitoring, transit station surveillance, as well as traffic management and control. In addition, current and (other) potential television transmission systems and their costs and potential manufacturers are considered.

The market analysis was conducted at the request of the Director of NASA's Technology Transfer Division. The purpose of the analysis was to assess the transferability of this NASA technology.

II CURRENT AND PROPOSED TRAFFIC SURVEILLANCE SYSTEMS AND RELATED TECHNOLOGIES UNDER DEVELOPMENT

The first traffic surveillance and control systems were installed in the early 1970s. These systems, in Los Angeles, Chicago, and Minneapolis, relied on magnetic loop detectors. More recent systems have included closed circuit television (CCTV) transmission. Some of the later systems existing in California, Michigan, and Ontario are described, as well as the Maryland DOT's proposed system. This section closes with descriptions of potential technologies for use in the future in the control of traffic flow.

Maryland Department of Transportation

Both the Washington Beltway and the Baltimore Beltway currently are equipped with telephone call boxes from which emergency aid or roadside service may be summoned. Along both beltways, boxes are spaced at 1-mile intervals. The Baltimore Beltway also has a number of variable message signs. (Message signs for the Washington Beltway are in the planning stage.) By responding quickly to calls for help and simultaneously displaying sign messages for other drivers, Maryland highway crews have attempted to alleviate incident-caused traffic congestion. Because of the possible time lapse before the call box is reached, however, traffic congestion still may be severe.

The Maryland DOT believes that a traffic surveillance system is needed and has developed plans to install one. The system design includes 60 television cameras to be located on Beltway overpasses, 3 miles of interconnected telephone cable (to be bought by Maryland), 9600-baud telephone line (to be leased from the Bell Telephone Co.), and a data compression capability to reduce the number of frames per second (without image degradation) to enable the use of telephone lines.

California Department of Transportation

The state of California has two traffic management systems partially installed. One system is on the San Francisco-Oakland Bay Bridge and the other on the Santa Monica Freeway.

The San Francisco-Oakland Bay Bridge traffic management system was designed "to improve the efficiency and enhance the user benefits provided by the (bridge's) tow service."[2] About 60 cars per day stall on the bridge, blocking lanes and causing delays totaling 3,000 vehicle hours. An average of 3 accidents per day also occur on the bridge.

The San Francisco-Oakland Bay Bridge traffic management system will include:

- 10 changeable message signs and sign controllers.
- Magnetic loop detectors at 1,200-ft intervals in all 10 lanes of the 8-mile bridge.
- 32 call box stations.
- 12 CCTV cameras hard-wired to a ready room on Yerba Buena Island where two pictures will be electronically selected for simultaneous transmission to the control center.
- An incident detection microcomputer, with added random access memory (RAM).
- An intelligent cathode ray tube (CRT) display controlled by a microcomputer.
- About 100,000 ft of coaxial cable.

An initial cost of $3 million for the system is estimated, excluding the magnetic loop detectors and call boxes that are already installed. The cost is high--$375,000 per mile. An additional $100,000 per year for operating and maintenance costs is anticipated. It should be noted, however, that a benefit-cost comparison made by the California DOT indicated that a $3 million saving would be realized in 10 years as a result of a reduction in accidents and time delays.

The Santa Monica Freeway traffic management system in Los Angeles, designed to reduce rush-hour congestion and incident response time, combines tow-service enhancement with ramp metering. This Santa Monica Freeway traffic management system is a demonstration project. The 12-mile east-west stretch of the freeway, when complete, will contain 14 single cameras, each having a 350-degree field of view capability and 0.43-mile view range. Images will be carried by microwave transmission, 20 to 60 ft above the roadway. Three channels will simultaneously provide three television pictures at the control center. The system, by Motorola, will cost in excess of $1 million, including cameras and displays.

Microwave transmission was selected as a cost-saving feature. Quotations received for coaxial cable ranged from $30,000 to $75,000 per mile ($360,000 to $900,000 for 12 miles). A system using microwave transmission is costed at $66,000 per mile for antenna, recievers, and transmitters for 14 camera sites. However, microwave transmission cannot be used in many urban areas because of the Federal Communication Commission's (FCC) restrictions on frequency allocations. In addition, microwave transmission requires straight-line links. For these reasons, the California DOT has negated plans to expand the system. (The entire freeway system in Los Angeles is approximately 600 miles long. At $66,000 per mile for microwave transmission, the total cost would be $39.6 million.)

Golden Gate Bridge Highway and Transportation District

Traffic on the Golden Gate Bridge (about 2 miles long, six lanes wide) is under surveillance and control by means of a low-light-level CCTV system. The CCTV system was installed several years ago and recently converted to low-light-level television. Imaging data are transmitted by means of coaxial cable to the control center at the toll plaza. Two cameras, one on each tower, cover the entire bridge. The system can handle four channels, although only two are currently used. Total cost for the system was about $80,000, most of which is in 1976 dollars. The system performs well and is well accepted. Surveillance of the bridge approaches is included in near-future plans.

Important to the Golden Gate system is a fleet of tow trucks owned and operated by the District. Response to traffic incidents is rapid and effective.

Michigan Department of Transportation

The traffic surveillance system in Detroit is primarily an electronic loop detector system although some televising capability exists. On the Edsel Ford Freeway (I-94), detectors are buried in all six lanes, every 1/3 mile, on 14 miles of highway. Smaller loop detector systems have been installed on the Chrysler Freeway (I-75 and I-375) and the John Lodge Freeway (U.S. 10). Only I-94 has telephone call-boxes, also located every 1/3 mile, and four television cameras at two locations (the I-375 and the U.S. 10 intersections). Eight additional camera sites are planned, for a total of 12. Michigan has avoided complex and expensive ramp metering systems. Detroit's simple ramp meters operate at one speed only (5-sec intervals) regardless of the time of day or the traffic volume on the freeway.

Emergency information is relayed to the freeway driver by means of variable message signs that are attached to the overpasses. Coaxial cables carry all signals. (The largest single expense to Michigan was the labor cost for digging trenches and laying the coaxial cable.) Traffic abnormalities are discerned by the computer, which alerts the operator at the Control Center by means of four TV displays. (Eight additional displays have been installed for future use.)

System components and their manufacturers are identified in Table 1. Cost for the entire system was $15 million in 1979, or about $469,000 per mile, including the variable message signs and loop detectors. The cost of the coaxial cable, including installation, exceeded $100,000 per mile.

Ontario Ministry of Transportation

The Queen Elizabeth Freeway in the vicinity of Toronto, Canada has a traffic surveillance and control system that was designed in-house

Table 1

COMPONENTS OF THE DETROIT TRAFFIC SURVEILLANCE SYSTEM

Component	Manufacturer	Model Number or Description
Loop detectors	Canoga	No. 402 and 404
Telemetry	Tocom	Specially modified equipment
Coaxial cable	General cable	Fused 3/4 inch type II
TV cameras	Diamond	B/W, LLL, 16-160 mm, zoom-tilt-pan
Field modulators	Tocom	5-30 MHz
Ramp controller	Siklos	Custom-made
TV monitors	Panasonic Sony	17 inches 22 inches
Computers (2)	Perkin-Elmer	No. 832
Line amplifiers	RCA	No. 152
Video cassette tape recorder	Gyrr	Modified time lapse; 50-216 MHz
Colorgraphic projector and display	Ramtek	

in 1974 to give ministry staff in-depth expertise in traffic surveillance technology. The system includes low-light-level CCTV. The entire system consists of 5 cameras, spaced a little less than 1 mile apart, 5 microprocessor-based ramp metering controls, 15 ramp and mainline induction loops, a central computer, a CRT graphic display, and a single broadband coaxial cable that is strung overhead. The system covers a 3.9-mile stretch of highway on the southern approach of Toronto. The highway contains three lanes in each direction.

Ontario has found the CCTV system to be a valuable tool for traffic and incident management, particularly because of close interaction with police. (The control center is located in a local police facility.) Public reaction to the system has been favorable. Early adverse reactions were related to the ramp metering which ostensibly was inequitable to the Toronto area residents during morning rush hours because their entrance onto the highway was constrained by current traffic flow. This complaint proved to be unfounded in that all ramp meters were adjusted when traffic flow slowed downstream.

Failures in the system have been minimal. Usually the cause of the failures was poor maintenance. In general, the Queen Elizabeth Freeway system has been well received by the Ministry and the public, and expansion of the system is planned.

High costs have not been considered a disadvantage to date. It should be noted, however, that the Toronto system is small--smaller than the system on the San Frnacisco-Oakland Bay Bridge. As the system is expanded, the high cost of coaxial cable may become an issue.

Related Technologies Under Development

Conditional Replenishment

A search of the United States Patent index revealed one patent, in addition to the NASA-JPL patent, that relates to traffic surveillance systems or to surveillance-types of telecommunications systems that could be applied to traffic surveillance. Issued in 1971, the patent describes an asynchronous time division multiplexing system for use with television signals ("Time Division Multiplexing of Video Redundancy Reduction Data Compressors," U.S. Patent 3,584,145, assigned to Bell Telephone Laboratories, Inc.). The primary objective of the invention is to reduce the time required for processing television signals and hence eliminate the extended interval for inactive images. The buffer memory in each redundancy reduction data compressor is asynchronously time-division-multiplexed to a transmission channel. The buffer memory stores a sample from a television signal only when that sample differs by more than a threshold value from a corresponding previously stored sample having the same time position in a television frame. The technique is now known as conditional replenishment.

Understandably, Bell Laboratories has a continuing interest in the transmission of television signals over conventional telephone lines. In 1980, Bell announced a new technique,[3] called motion-compensated coding, which takes conditional replenishment one step further. Motion within a scene is estimated and then compared with successive frames that are spatially displaced by that motion. If the estimate is accurate, the intensity difference between the original point and the point to which the object has moved is less than the intensity difference at the same location of the two successive frames; consequently, less information is needed for transmission. Thus, less information (1.5 million bits per second compared with 64 million bits per second for standard television) is needed for transmission. According to Bell researchers, motion-compensated coding provides a picture that is "acceptable for videoconferencing, but not for television transmission where excessive motion is evident." Excessive motion, such as that seen on highways, causes a blurring of the picture.

Fiber Optics

Fiber optics has attracted considerable attention as a means of television transmission. The state of the art has reached the level of maturity necessary for application to traffic surveillance and control. With fiber optics, light instead of electricity is used to transmit voice and video images by bundles of fine glass fibers. Images

are converted/coded into pulses of light at the rate of 44.7 megabits/sec. The fibers carry laser signals over long distances; for short distances, light-emiting diodes (LEDs) are used.

Fiber optics is applied primarily to point-to-point information transmission through a high bandwidth (potentially higher than microwave radio), low-loss medium. For the 1980s, the high bandwidth promises a capability for integration of multiple communications on one fiber. Initial capital costs for fiber optic systems also are expected to be high.

The largest near-term market for fiber optics is the telephone. In fact, several developers of integrated data transceivers already offer fiber optic links as features within existing product lines. Although handled in a manner similar to coaxial cable rather than twisted-pair cable, the optical cable can be buried, acrially mounted, or ducted. Improvements, however, are still needed in both instrumentation and techniques. Further development of laser sources, photodetectors, and optical couplers is needed according to the Harris Government Information Systems Division of Melbourne, Florida.[4] Companies such as AMP, Incorporated of Harrisburg, Pennsylvania are making progress in developing fiber optic connectors that overcome the coupling mismatch problem. (Mismatches between light sources, detectors, and fibers can sap optical transmission power.)

Of note is AT&T's limited use of fiber optics to date. Currently, only one telephone system includes fiber optics: Within the Bell system in Chicago, 144 fibers can transmit 50,000 telephone conversations (not television) simultaneously.[5] Manufacturers of fibers for video transmission included Belden Corporation whose cables are incorporated into the Sperry Univac video frequency data link for the city of Houston. The fiber optics link a management information system (MIS) computer in Houston's Municipal Courts Building with 5 video terminals in the main library more than 10 miles away. Honeywell has joined with Du Pont and ITT Cannon to produce HDC (Honeywell-DuPont-Cannon) interface components. Although 2 years older than the HDC, Belden fiber optics can claim many advantages (see Table 2).[5] Motorola's fiber optic ferrule semiconductor fits into AMP's connector for efficient optical coupling. Other companies include RCA, 3M, Tektronics, Bell & Howell, Hewlett-Packard, Orionics, and Laser Diode.

The market to date for fiber optic systems has resided almost exclusively in custom-designed components to be integrated into existing nonoptic systems such as standard telephone lines. Users have included manufacturers of telecommunications systems; Army, Navy, and Marine facilities; transportation agencies; utility companies; financial institutions; libraries; and oil refineries. Sales in 1979 approached $13 million, primarily for voice transmission.

Costs for fiber optic systems range from $2 to $5 per foot in lots of 1,000, or $10,400 to $26,400 per mile, plus an initial cost of $50,000 to $100,000 for repeaters and other equipment.[6] It should be noted

that fiber optics requires costly trench installation, similar to that of coaxial cable.

Table 2

COMPARISON OF BELDEN AND HDC FIBER OPTICS

1978 Belden Fiber Optic Advantage	1980 HDC Fiber Optic Advantage
Small size and light weight	Light weight and small dimension
Flexibility and high strength	Cable flexibility compared with wire
Large bandwidth for size and weight	Data rates to 30 Mb per sec
Longer cable runs between repeaters	Optical path lengths to 30 meters
Electromagnetic, crosstalk immunity	Immunity to electromagnetic interference
Nuclear radiation resistant	Use standard electrical connectors
No electrical hazard, cut, damaged	Simple fiber termination at diode connector
Potential high-temperature operation	Compatible with high-density packaging
No arcing in combustible atmosphere	TTL and CMOS compatible output
No ground loop or short circuit problem	Cost less than existing fiber optic links
Immunity to lightning discharge	HDC interface requires little extra design

Note: Entries taken nearly verbatim from Belden and HDC statements.

Source: Reference 6

Discussions with traffic and research engineers in several states, however, revealed a reluctance to trust fiber optics. The problem relates primarily to the industry, which according to California DOT engineers is not ready. These engineers will not consider investing in a fiber optics system until the manufacturers are well established and have interchangeable equipment, a condition not expected for many years. According to these same engineers, the injection lasers and receivers of different manufacturers have different performance criteria with regard to temperature sensitivity and other parameters.

Further discussions with the California DOT engineers revealed a cessation of interest in any microwave technology, with or without satellite links, because of the high cost--more than $50,000 per mile--and the licensing requirements. The long waiting period for an updated picture was the primary strike against slow scan television transmission.

III NASA'S COMPRESSED TELEVISION TRANSMISSION

The NASA-JPL CTT technology is based on a space communications system that incorporates a concatenated Reed-Solomon-Viterbi coding channel [U.S. Patent 3,988,677 awarded to NASA (R. F. Rice) on October 26, 1976]. The space system transmits compressed data from a spacecraft to a data processing center on eath. Imaging data are compressed into source blocks that are coded by a Reed-Solomon coder and interleaver and a convolutional encoder. A Viterbi decoding is followed by a Reed-Solomon decoding and deinterleaving. The output is then decompressed and processed to reconstruct the original image. The primary benefit of this on-site coding is significant error reduction. The patent is provided in full as Appendix A.

Two additional efforts by R. F. Rice of NASA-JPL on channel coding and compression of planetary imaging data are documented in NASA-CR-140181, "Channel Coding and Data Compression Systems Considerations for Efficient Communications of Planetary Imaging Data," dated September 1, 1974 and in NASA-CR-157343 "RPV Application of a Globally Adaptive Rate Controlled Compressor," dated July 15, 1978. (See Appendix B for document abstracts.) Appendix C provides a paper that describes the NASA-JPL rate-controlled image data compression developed for the Galileo orbiter mission of Jupiter.

The proposed NASA traffic surveillance system transmits television images over telephone line digital data links by means of a low-cost data compressor/decompressor with error protection coding. The system consists of 7 components: 2 at the television camera site (the code computer and semiconductor, plus the camera), 4 at the control center (decoder minicomputer, video digitizer, display driver, television monitor), and 1 between sites (the modum to the telephone line). (See Figure 2.) Each interface unit will handle two-way communication between the camera site and the center. That is, in addition to receiving data,

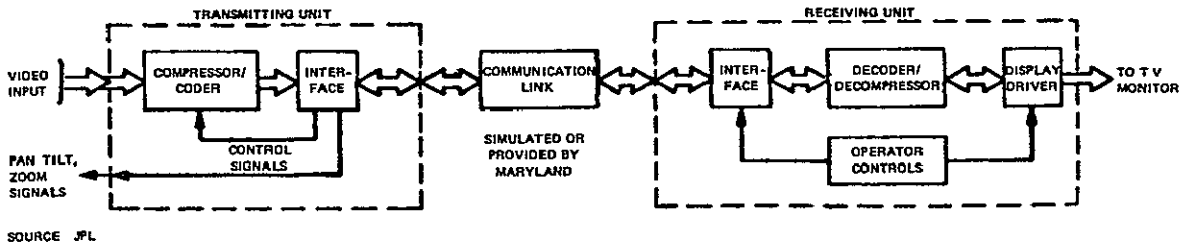
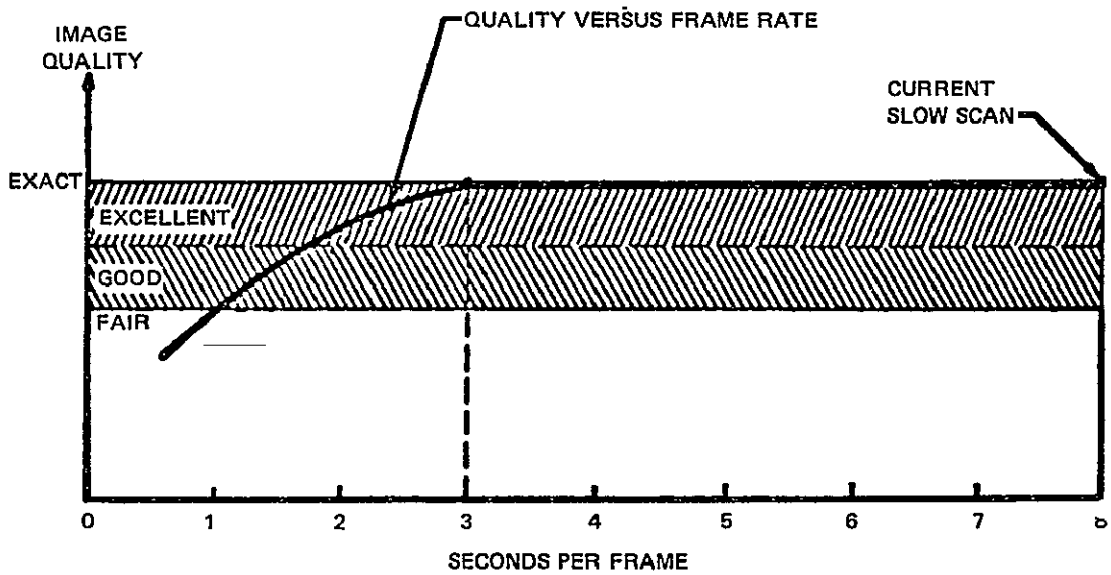


FIGURE 2 COMPRESSED TV TRANSMISSION SYSTEM COMPONENTS

the control center will send signals to control the television frame rate and the pan, tilt, and zoom of the camera. The operator is given great flexibility to adapt the rate/fidelity priorities. All or most of the components can be obtained readily off-the-shelf (e.g., microprocessor chips and associated equipment). The system is compatible with a videcon camera and will be compatible with a solid-state, charged coupled device (CCD) for imaging in the future.

Block coding is used to enable error correction (not just detection) at the receiver end. Each block is coded; the decoder corrects errors made in transmission.

The data compression algorithm is rate-controlled. By accepting degradation of image quality (i.e., some blurring), the operator can obtain high frame rates. The slower the frame rate, the better the image quality. Good quality is possible at speeds of 3 sec per frame. (See Figures 3 and 4.) Acceptable quality is possible at 1 sec per frame. A comparison of compressed television imaging with slow-scan averaging is provided in Figure 5.

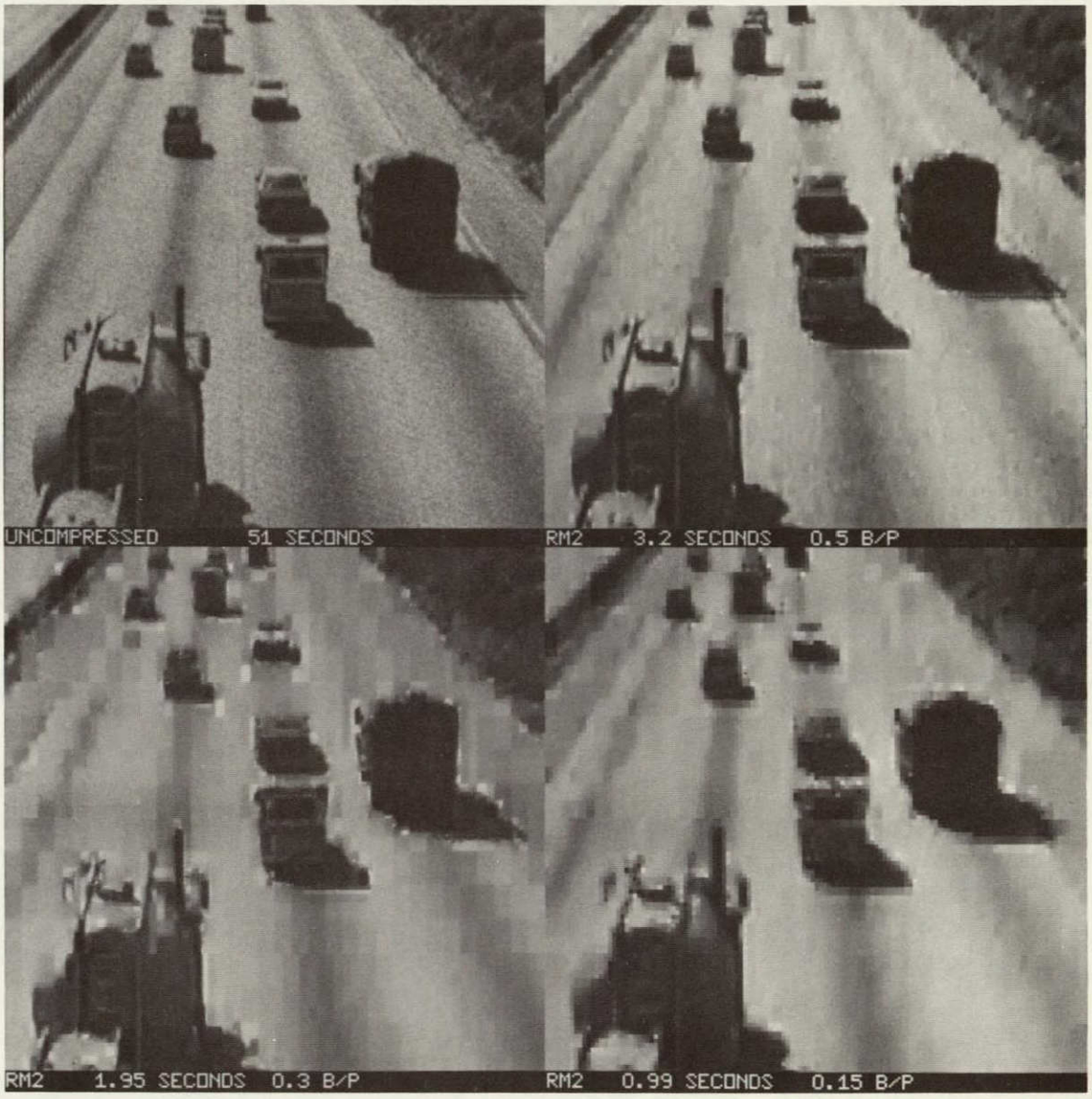


SOURCE JPL

FIGURE 3 FRAME RATE VERSUS QUALITY TRADE-OFF

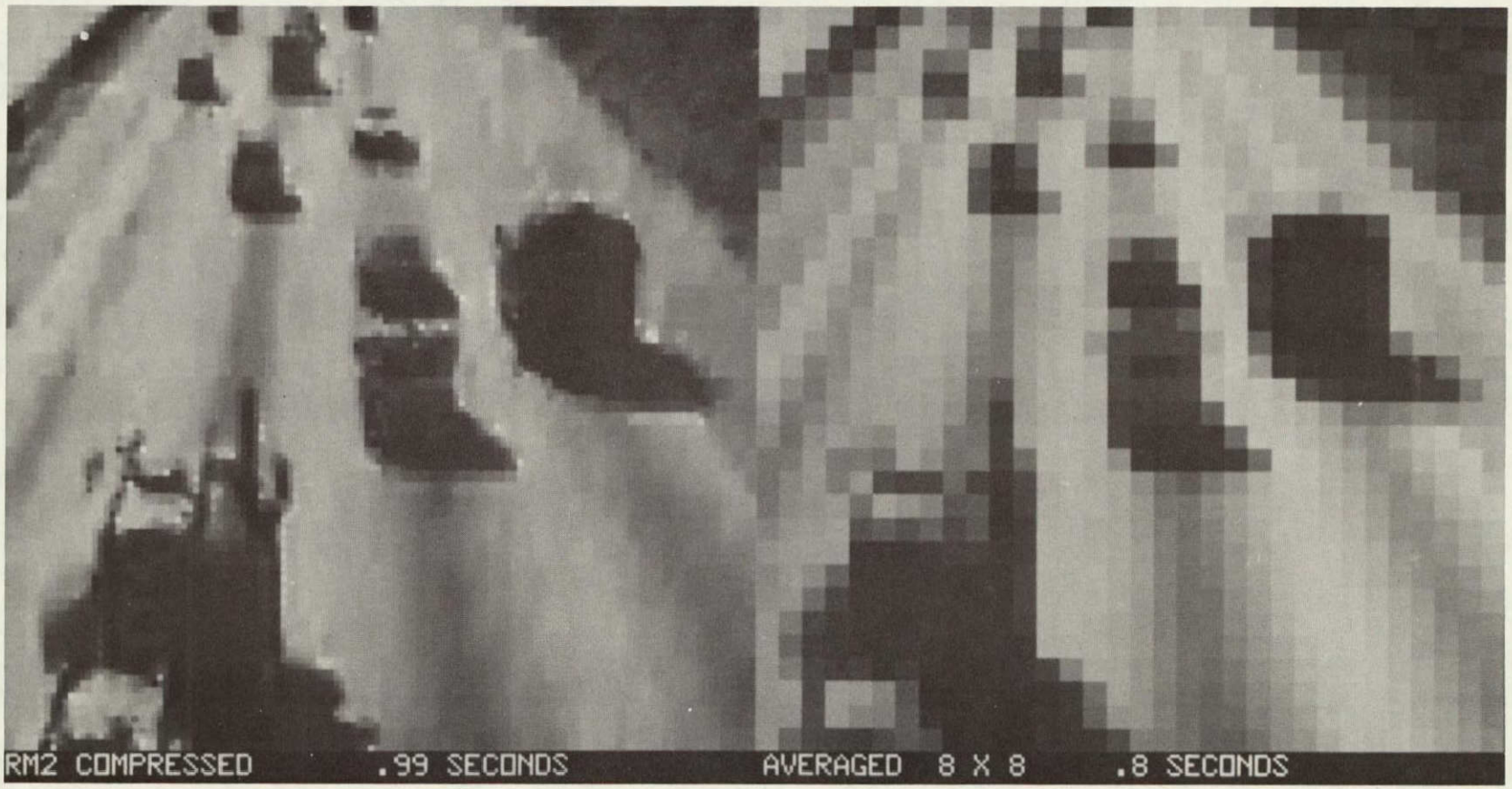
The use of telephone lines for data transmission should mean much lower costs. Less than $10,000 per mile is estimated by JPL for CTT using telephone lines as compared with $30,000 to $70,000 for other systems. An agreement with the particular telephone company is necessary. Data compression makes possible the use of telephone lines that cannot handle the high data rates of live television.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



SOURCE: NASA-JPL

FIGURE 4 COMPARISON OF COMPRESSED TELEVISION (RM^2) IMAGES WITH UNCOMPRESSED IMAGES



SOURCE:

FIGURE 5 COMPARISON OF COMPRESSED TELEVISION IMAGES (RM^2) WITH SLOW-SCAN AVERAGED IMAGES AT A SPEED OF APPROXIMATELY 1 SECOND PER FRAME

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

IV CTT POTENTIAL MARKET

The CCT system is a surveillance system. Therefore, anything that needs to be watched is potentially a candidate for CTT. The applications discussed below are the applications that will likely benefit by use of the system today. Many other applications may surface, however, as the system's unit cost decreases and as the cost of labor that can be replaced by the system increases.

The CTT system is being developed by JPL specifically for highway traffic surveillance. From discussions with several major manufacturers (i.e., Nippon Electric Corporation, Robot, TRW, Colorado Video, and Dalmo Victor), traffic surveillance appears to be an excellent application of the system and should prove to be very beneficial, but it is not necessarily the best application. The two applications that appear to have a high potential for CTT use are business teleconferencing and remote medical diagnosis.

Teleconferencing

Several businesses already have leased slow-scan systems (78 sec/frame). They have all experienced the same problem with existing systems: the slow system rate takes some adjustment. In some cases, the businessmen adjusted well to the system. In other cases, the men were unable to adjust and consequently rejected the system. The primary objection was the long waiting period for an updated picture. The NASA/JPL CTT system (1-3 sec/frame) is expected to eliminate that concern. It should be noted, however, that systems approaching real-time (1/30 sec/frame) are being commercially produced. Compression Labs Inc. is marketing such a system, but it requires a special high-bandwidth telephone line at a monthly rental cost of about $40,000.

The use of CTT in business teleconferencing is very promising. The increasing burden of travel on management is causing the major corporations to seek alternatives. ARCO recently announced plans for a $20 million video conferencing network that will offer one or more of the following capabilities at 110 of its offices: electronic mail, facsimile transmission of documents, computer-to-computer data transmission, as well as video conferencing.

Video teleconferencing will unquestionably be cost-effective for at least the top 500 companies in the United States according to Richard F. Bader, President of Compression Labs Inc. His statement is in reference to systems costing $60,000 to $300,000 per pair.

If the cost can be reduced by an order of magnitude by a cost-reducing compression system, the overall market for business telecommunications would be even more. The limiting factor in its widespread use may be disgruntled middle managers. From a recent survey of 1,000 middle managers, Gnostic Concepts Inc., a Menlo Park consulting Firm, concluded that this group of managers will object vehemently to video conferencing. According to industry experts, resistance will arise because employees still associate travel with status and view it as a higher value to the corporation. On the other hand, Paul Snyder, vice president responsible for the new network at ARCO, is convinced that once ARCO managers become aware of what the system can do, most of them will not only accept it, but also find new ways to use it.

SRI has made a conservative estimate that a market exists for 750 telecommunications systems.

Remote Medical Diagnosis

Remote medical diagnosis is being used successfully in Canada. With a slow-scan system, Canadian doctors are now able to visually diagnose patients who live in remote areas, close to a teleconferencing center, but hundreds of miles from any hospital. This type of service could become a valuable medical tool if extended to all hospitals. Rare or baffling diseases could be diagnosed by experts across the country. In fact, X rays and even microscopy are being transmitted successfully by today's slower systems (transmission rates of 78-150 sec/frame) between 25 to 50 hospitals and approximately 300 radiologists in the U.S.

Approximately 7,000 hospitals operate in the United States today. The use of a teleconferencing system, at least for sending X rays in many of these hospitals is likely. Once this use is proved to be cost-effective, many other hospital applications should be possible.

Patient Monitoring

Intrahospital use is another hospital application for video monitoring as many patients need continuous observation. Either a standard, real-time, closed-circuit system or the CTT system could significantly reduce hospital costs. To decide which system to use, a cost-benefit analysis for each hospital should be done. Currently, sitters are employed to watch patients in their rooms. No more than two patients are assigned per room; theoretically, therefore, two is the maximum number of patients a sitter can watch. However, the severe shortage of nurses and the high financial burdens necessitate that hospitals use one sitter for two rooms, but vigilance of the patients is thereby reduced.

Hospitals are currently using closed-circuit video monitors for only three purposes: security of the miles of hallways, observation of psychologically disturbed patients, and education. San Francisco General Hospital illustrates the potential for this application. The hospital has 500 staffed beds (generally 70% occupancy), 300 registered nurses, 100 licensed nurses, and 100 orderlies. A hospital this size has many patients that require constant observation: approximately 10-15 patients must be watched for suicide precaution, about 20 criminal patients are under security by policemen, and 10-15 patients in the intensive care unit must have a nurse on hand at all times. All of these patients are now watched by sitters or nurses. Yet, except for those in intensive care (these patients need constant treatment until their condition stabilizes), all could be monitored remotely. Therefore, 40-50 patients, or about 15% of all patients, could be observed by the CTT system.

The primary objection to use of a video system in hospitals (other than financial) is the lack of human contact and the unnerving feeling patients may have from being watched by a camera. This should be a serious consideration for only the suicidal patients; the others are generally unconscious and would not be adversely affected by remote observation.

Contrary to expected good interhospital use, however, intrahospital applications are not very promising. The CTT system is at best only marginally cost-effective compared with bedside personnel costs, even in the large hospitals such as San Francisco General. As such, few hospitals will use the system for observation purposes. Only an increase in the nurse shortage would cause the hospitals to use the system. It is important to note that this pessimistic view of the hospital as a potential market for CTT is only an early indication. A complete cost-benefit analysis for hospitals should still be done, especially if the hospital is interested in the system for remote medical diagnosis.

Education

The CTT could also have many educational applications. Lectures could be transmitted from major universities to companies around the country, industries could visually demonstrate a process or technique to interested people nationwide, and doctors could more easily promote medical advances and breakthroughs in surgical techniques. Essentially, any educational or training service, instead of being limited to local people could be expanded to serve people anywhere.

According to Mr. Robert Kinchlow, director of Stanford University's telecommunications, however, the CTT system will have a very small market in the educational field. Although there is a real need for continuing education in industry, that need is being satisfactorily filled. For example, Stanford lectures are transmitted throughout the Bay Area by microwaves and distributed throughout the nation on video tapes. The only limitation to video tapes is for case study courses;

however, in this situation, real-time monitoring is more desirable than a slow scan system anyway.

Defense

A major user of the CTT system may be the military. In addition to the numerous air fields and bases that the military would like to observe more closely, many remote sites also must be guarded that have no personnel on hand. To guard these remote sites, the military is using low-bandwidth sensors that tend to generate many false alarms. The cost of reacting to these false alarms is excessive. Reducing false alarms by the use of a visual transmission of the site should result in significant cost savings. Approximately 250 military bases in the United States could benefit from CTT surveillance.

Traffic Management and Control

Discussions were held with representatives of 11 state highway departments. Table 3 lists the 11 departments, their current systems, and interest in NASA's CTT. Nine of the 11 expressed varying degrees of interest in the NASA system. The remaining two have no interest in any traffic surveillance system due to budgetary constraints. Many departments believe that the future of the NASA system will be determined by the cities where traffic congestion is most severe. The application most often mentioned was the interstate highway that approaches or penetrates a metropolitan area. Of primary interest to all departments is the system's combination of a high frame rate and low cost.

Projecting to all states the degree of interest in CTT for traffic management indicated from a survey of 11 states gives an estimate of the total market. That is, 9 of the 11 states surveyed indicated a potential market, and those markets represented 1 to 4 systems each (an average of 1.3 systems per state); therefore, the total potential market could be 53 systems. The high cost for a traffic management system given as the reason many states have installed no system to date should be alleviated with the NASA CTT and further strengthen the market projection.

Emergency Traffic Management

Emergency management might also benefit from traffic surveillance and control. Interest has been expressed by at least one emergency response unit. California's Office of Emergency Services realizes that the major highways and arterials must be unblocked to ensure escape routes for civil defense units or in case of a natural disaster such as an earthquake, flood, or volcanic eruption. The state has already begun an informal investigation of surveillance techniques, but this market is too uncertain to estimate a sales figure.

Table 3

TRAFFIC MANAGEMENT SYSTEMS IN USE AND INTEREST IN CTT
IN SELECTED STATE HIGHWAY DEPARTMENTS

State DOT	Current Systems	Potential Interest in CTT	Comments
Connecticut	None	None	Budget constraints
Kansas	None	Yes	Potential need in 2 urban areas
Kentucky	None	Yes	
New Jersey	Inductive loop system on New Jersey Turnpike	Yes	
New Mexico	None	Yes	Would like additional information
New York	CCTV in Hudson River tunnels, inductive loop system planned for Long Island	Yes	
Oklahoma	None	No	
Oregon	None	Yes	
Pennsylvania	None	Yes	Potential needs exist on 4 major highways
Texas	CCTV in Houston	Yes	Houston system inoperative due to cable problems
Washington	CCTV in Seattle	Yes	System expansion planned

Airport Surveillance

Accidents on airstrips and at airport ramps are not uncommon. Whether an accident results from the collision of two aircraft or of an aircraft and a maintenance vehicle, the loss of time and dollars is high. NASA and SRI believed that many airport accidents could be aborted if television surveillance systems were installed. Therefore, contacts were made with airport officials of six states to determine potential interest in television surveillance of airports, particularly compressed television transmission. The responses are documented below.

- California has some interest in a surveillance system to monitor traffic volumes, according to the Deputy Chief of the Aeronautics Division. However, budget constraints negate any near-future plans.

- Connecticut's Manager of Airport Operations expressed an interest in after-the-fact accident monitoring and in detecting foreign objects, but questioned the advisability of telephone line transmission.

- In Georgia, a concern was expressed regarding radio frequency availability to relay warnings to aircraft and maintenance personnel. The frequency at Atlanta International Airport has about reached the point of overloading.

- The Ohio Division of Aviation believes that the value of a television surveillance system would be limited to documenting the events leading to an accident for use at public hearings. In fact, acceptance by the pilots' unions of any surveillance system is considered doubtful.

- In Pennsylvania, television surveillance is viewed by the Bureau of Aviation's Airports' Engineer as an effective security measure, particularly for remote areas of the airfield, but is not considered effective for accident prevention.

- According to Chicago's Chief of Airport Operations, ramp and airfield surveillance would not be cost-effective at the O'Hare and Midway Airports. Both airports have configurations that would require the installation of many television cameras. As an added dis-incentive, airport telephone lines already transmit weather data as well as the data collected by all airport instruments. Line capacity has been reached.

From the above documentation, SRI has concluded that a market for compressed television transmission for airport/airfield surveillance would be small--limited to accident documentation in those airports having the approval of the local pilots' union and to remote airstrip surveillance.

Transit Station Surveillance

A study conducted by Dunlap and Associates, Inc. for the Transportation Systems Center* revealed that closed circuit television (CCTV) systems have been installed in many transit stations. Some have been connected to automatic sensor alarm networks and automatic response capabilities, such as remotely controlled gates and locks for both safety and security. The presence of the cameras has contributed to increased ridership due to passenger confidence in station safety.

Transit station environments (e.g., low light, vibration, dirt and dust, electrical power and moisture) present special problems for CCTV hardware. Cameras and video-signal transmission lines must be selected and located with these environmental factors in mind.

Properties that have station surveillance systems include the Bay Area Rapid Transit District (BART) in San Francisco/Oakland, the Chicago Transit Authority, the Massachusetts Bay Transportation Authority (MBTA) in Boston, and the Southeastern Pennsylvania Transportation Authority (SEPTA) in Philadelphia. Telephone interviews were held with representatives of the four properties.

All BART stations are equipped with television surveillance systems. Images are transmitted by means of coaxial cable. BART officials reportedly have expressed concern over the high cost of coaxial cable and would be interested in telephone line transmission, provided image clarity and transmission time are satisfactory.

Philadelphia began installing television surveillance systems in its stations in 1976. The Authority has approximately 40 stations, 3 of which are currently equipped with slow scan TV cameras (as many as 25 per station) and one-way audio communication. Images are transmitted by means of telephone lines. Plans are under way to provide television surveillance in 20-30 stations, and a contract has been let to Westinghouse.

Chicago has 2 broadband television surveillance systems, with coaxial cable image transmission, serving less than 10 transit stations. One system has an 8-mile distribution on 70 channels. (Maximum capability is 120 channels.) Two-way audio communication with troubled passengers is possible by means of 4,000 speakers within the stations. The cameras zoom in to the site of the communication initiator. The central monitor is installed at the Chicago Police Department headquarters. Although costs are high, Chicago appreciates the systems and is looking forward to providing television surveillance in all 140 stations by 1990.

---

*Bloom, Richard F., "Closed Circuit Television in Transit Stations: Applications Guidelines, "Dunlap and Associates, Inc., Darien, Connecticut, Report No. UMTA-MA-06-0048-80-5, August 1980

In Boston, only one station has been equipped with a closed circuit television surveillance system (with coaxial cable transmission). Braintree Station was opened in 1979 on the MBTA's newly expanded railway. CCTV surveillance was included in the Federal construction specifications. Central controls are located at the Braintree Police Department. Interest is equipping all stations is high; however, because of budgetary constraints, CCTV installations are not included in current plans.

A brief call was made to the Office of the Director of Safety of the New York City Transit Authority (NYCTA), which is testing television surveillance systems at two stations. (NYCTA is by far the largest transit property in the United States with 458 stations, including 265 subway stations.) A determination of performance and user satisfaction appears to be premature. Cost savings would certainly be of interest, however, since here again budgetary constraints are real.

Based on information acquired from the five above-mentioned transit properties, SRI has concluded that a sizeable market exists for television surveillance of transit stations. Each of the properties expressed a desire to provide a surveillance capability at its stations. Budgetary constraints appear to be the primary limiting factor. With the decreased cost of compressed television transmission, the constraints may be eliminated in some cases.

The resulting market, including existing properties and planned properties and property expansion, could be as large as 820 stations by 1990:

456	NYCTA
132	CTA
57	MBTA
15	SEPTA
40	Washington Metropolitan Area Transit Authority (expanded system)
20	BART (expanded system)
100	New properties in Baltimore, Miami, and other cities
820	

V POTENTIAL MANUFACTURERS

The SRI Team contacted five manufacturers of slow-scan television systems to determine their interest in the NASA/JPL CTT technology. All of them expressed considerable interest in it.

Robot Corporation, San Diego, CA sells slow-scan systems exclusively. It has been in the business since 1969, has 30 employees, sells 200 units per month, and generates about $2 million gross per year. The company has systems that transmit at between 2-70 sec/frame at varying degrees of clarity. The standard transmission of 256 × 256 lines takes 35 sec. President David Smith believes that Robot is by far the most capable slow-scan producer, with better systems and far greater sales volume than any other commercial company in the country. Mr. Smith does not believe that compression of the transmission will be cost-effective for 5-10 years, but is extremely interested in any technical development.

The Broadcast Division of Nippon Electric Corp. (NEC), Poway, CA has 50 employees and sells two systems. NEC has an analog system on an FV carrier that requires 30 sec/frame of information and a digital color system that delivers 4.8 kilobytes of information in 150 sec over a standard voice-grade telephone line with no loss of resolution. NEC's digital system can send 1.54 megabytes in real time, with some degradation of quality. The company has sold about 10 large systems to such organizations as NASA, Ford, and IBM. Nippon is aware and confident that a market exists, especially in teleconferencing and as a medical tool.

Colorado Video in Denver, established in 1965, has 40 employees and has sold about 90 slow-scan television systems in the past 13 years. The slow-scan system is the primary product. Prices range between $11,000 and $22,000. The Colorado Video system uses no compression and as such achieves about the maximum transmission rate of 78 sec/frame over the voice-grade telephone lines. As reported, Colorado Video sees a market in the following areas: remote medical diagnosis, business teleconferencing, educational transmission to remote locations, and security of remote sites. Colorado Video is the main competitor of Robot according to Robot's president.

Dalmo Victor, Belmont, CA produces many instruments for military applications and until recently produced slow-scan television equipment. It has recently become interested in JPL's CTT system and would like to see a simulation to determine how well the system works.

The Electronic Systems Division of TRW in Redondo Beach, CA is engaged in the "creative," early development of advanced image processing systems. TRW is investigating slow-scan systems mostly for military applications because all of its work is under government contract. It does no commercial marketing of products.

VI CONCLUSIONS

Although still small in number, television-based traffic surveillance systems are growing in favor with highway engineers. Since the mid-1970s, all new installations have included television transmission. Imaging data are transmitted by coaxial cable at a cost of $30,000 to $75,000 per mile of highway, depending on labor costs, or by microwave at a cost of $50,000 per mile. A need for a reduction of data transmission costs has directed attention to the use of telephone lines. Clarity of the imaging data that must be compressed to accommodate telephone line digital data links, however, has been sacrificed as has fast transmission time. NASA's data compression/decompression technology with error protection coding, developed at JPL for a space communications system, promises to overcome the problem of image degradation and thereby make possible a transmission cost of less than $10,000 per mile.

To ensure commercial viability of the NASA-developed system, the market must not be limited to traffic surveillance. A survey of potential users revealed a large market for teleconferencing equipment to replace slow-scan systems (78 sec/frame), for medical equipment to monitor patients and enable remote diagnoses, and for surveillance of remote military sites.

SRI believes that the maximum 10-year market projection for CTT systems derived from its survey of potential users, would be about 5,390. This projection represents about 3,500 hospitals, 70 urban areas, 750 coporations, 820 transit stations, plus 250 military sites. A more realistic projection would be 539 systems, i.e., 10% of the maximum. Costs should range between $20,000 to $600,000 depending on size, with an average cost of about $50,000. Thus, sales expectancy for 10 years would be $27 million, or $2.7 million per year.

Discussions with seven manufacturers of slow-scan television and related equipment revealed a real interest in the NASA CTT technology with its 1-3 sec/frame compression/decompression rate. In addition, (based on their experience), they have some conviction that a significant market exists for it.

A review of emerging technologies revealed no means for transmitting imaging data that appeared to be cost-effective in a small system. Fiber optics transmission requires a large initial capital outlay for trench installation. In addition, because of differing performance criteria of different manufacturers for injection lasers and receivers, equipment is not interchangeable and therefore not yet acceptable to potential users of traffic surveillance and control systems. Bell Laboratories' conditional replenishment/motion compensated coding is ineffective for rapid-motion subjects such as highway traffic and intruders. Thus it may compete for the teleconferencing market, but not the market for surveillance instrumentation.

From its survey of potential users and manufacturers, we conclude that a significant market does exist for the NASA-JPL CTT system and that competition from an emerging technology (i.e., fiber optics) is not expected for a minimum of 5 years. The CTT system should be ready for commercial introduction worldwide in less than 3 years.

REFERENCES

1. Transportation Research Board, "Freeway Traffic Management" (September 1979).

2. State of California, Department of Transportation, "Project Report for a Traffic Management System on the San Francisco-Oakland Bay Bridge" (October 24, 1978).

3. "New Developments: Compression Allows Video Transmission on Telephone Lines," Industrial Research and Development (October 1980).

4. Carothers, G. Harlan, Jr., "Fiber Optic Communications," Microwave Journal, 22, 1 (July 1979).

5. Kent, Leticia, "Tripping the Light Fantastic," Sci Quest (February 1980).

6. Bailery, S. J., "Fiber Optics Firms Tailor to Suit Plant Floor Needs," Control Engineering (August 1980).

Appendix A

U.S. PATENT DESCRIPTION

ORIGINAL PAGE IS
OF POOR QUALITY

United States Patent [19]

Fletcher et al.

[11] **3,988,677**

[45] **Oct. 26, 1976**

[54] **SPACE COMMUNICATION SYSTEM FOR COMPRESSED DATA WITH A CONCATENATED REED-SOLOMON-VITERBI CODING CHANNEL**

[76] Inventors: **James C. Fletcher**, Administrator of the National Aeronautics and Space Administration, with respect to an invention of **Robert F. Rice**, South Pasadena; **Edward E. Hilbert**, Tujunga, both of Calif.

[22] Filed: **June 23, 1975**

[21] Appl. No.: **589,173**

[52] U.S. Cl. . **325/41**; 340/146.1 AL, 340/146.1 AQ, 340/146.1 AV

[51] Int. Cl.[2] **H04L 1/10**

[58] Field of Search 325/41, 4, 38 R, 358/3, 179/15 AE, 15 AP, 15.55 R, 15.55 T, 15 AC, 340/146.1 AL, 146.1 AQ, 146.1 AV

[56] **References Cited**

UNITED STATES PATENTS

3,831,143 8/1974 Trafton 340/146.1 AV

OTHER PUBLICATIONS

Hybrid Coding Systems Study—J. P. Odenwalder et al.—Linkabit Corp. Sept. 1972—NASA CR 114,486, Final Report

"Practical Applications of Coding"—I. M. Jacobs, May 1974—IEEE Trans. on Info. Theory, vol. IT-20, No. 3—pp. 305-310

"Burst Correcting Codes for the Classic Burst Channel"—G. David Forney, Jr. Oct. 1971—IEEE Trans. on Comm. Tech., vol. COM-19 No. 5, pp. 772-780

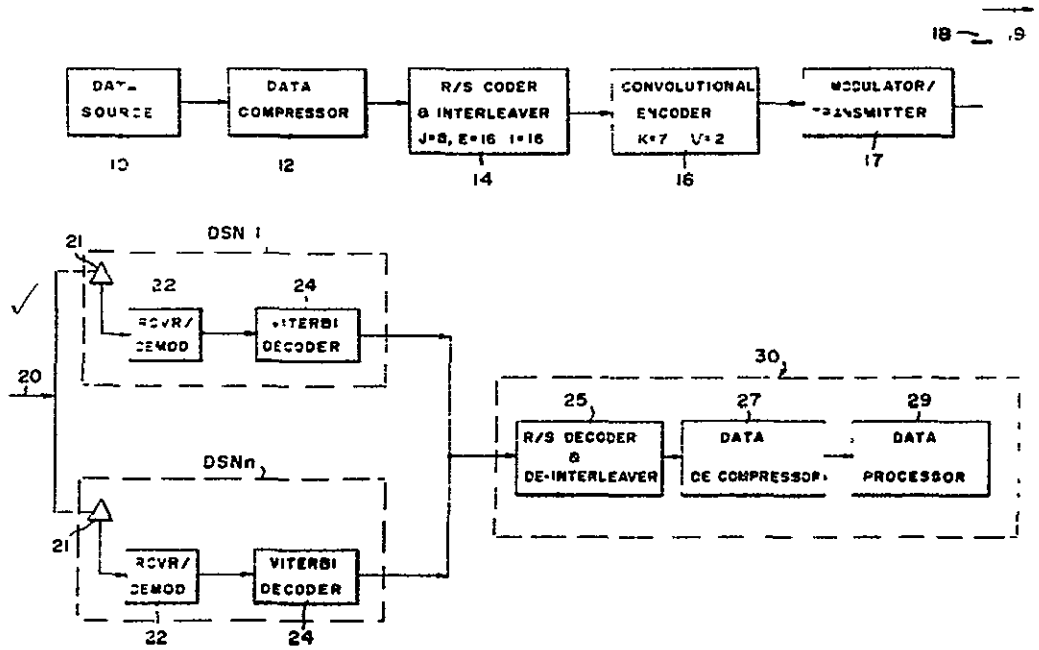
"A Hybrid Coding Scheme for Discrete Memoryless Channels"—D. D. Falconer, Mar. 1969—BSTJ pp. 691-702, 716-718

Primary Examiner—Robert L. Griffin
Assistant Examiner—Marc E. Bookbinder
Attorney, Agent, or Firm—Monte F. Mott; Paul F. McCaul; John R. Manning

[57] **ABSTRACT**

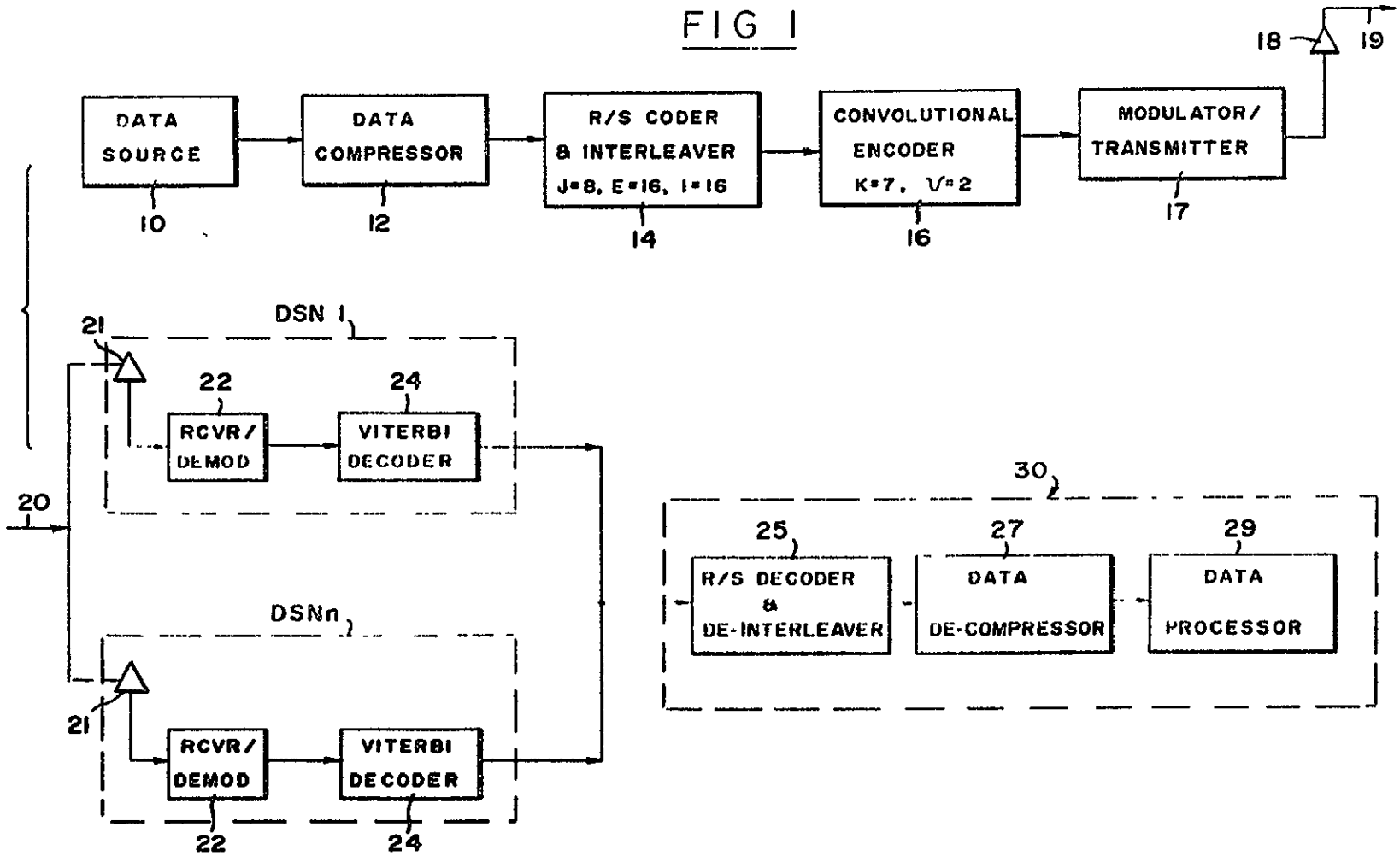
A space communication system incorporating a concatenated Reed Solomon/Viterbi coding channel is disclosed for transmitting compressed and uncompressed data from a spacecraft to a data processing center on Earth. Imaging (and other) data is first compressed into source blocks which are then coded by a Reed Solomon coder and interleaver with parameters J=8, E=16, I=16, followed by a convolutional encoder of parameters $k=7$, $\nu=2$. The received data is first decoded by a Viterbi decoder followed by a Reed Solomon decoder and deinterleaver. The output of the latter is then decompressed, based on the compression criteria used in compressing the data in the spacecraft. The decompressed data is processed to reconstruct an approximation of the original data-producing condition or images.

10 Claims, 10 Drawing Figures



Reproduced from best available copy

FIG 1


DATA SOURCE
10
DATA COMPRESSOR
12
R/S CODER & INTERLEAVER J=8, E=16, I=16
14
CONVOLUTIONAL ENCODER K=7, V=2
16
MODULATOR/ TRANSMITTER
17
18
19
20
21
DSN 1
22
RCVR/ DEMOD
24
VITERBI DECODER
DSNn
21
22
RCVR/ DEMOD
24
VITERBI DECODER
30
25
R/S DECODER & DE-INTERLEAVER
27
DATA DE-COMPRESSOR
29
DATA PROCESSOR

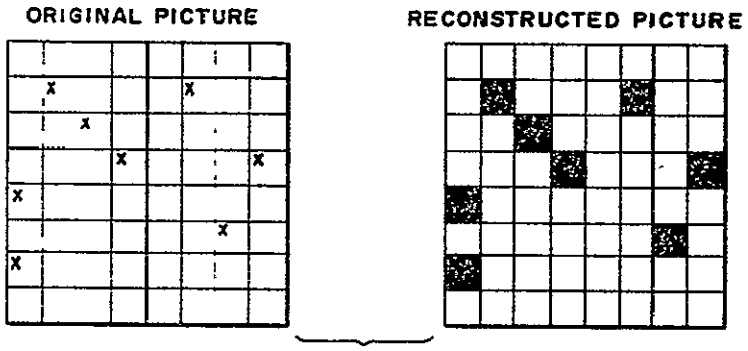

ORIGINAL PICTURE
RECONSTRUCTED PICTURE

FIG. 2

FIG 3

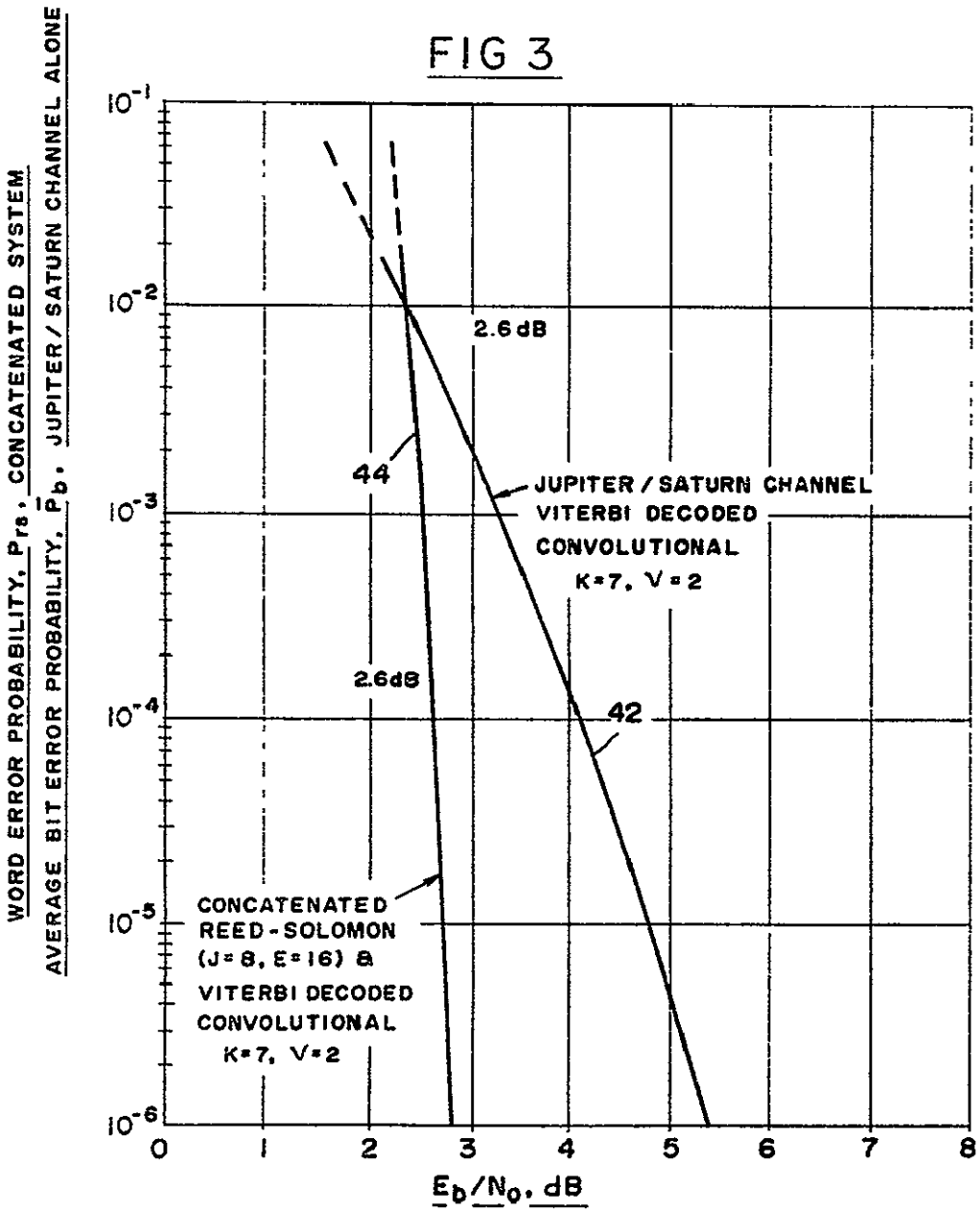

WORD ERROR PROBABILITY, P_{rs}, CONCATENATED SYSTEM
AVERAGE BIT ERROR PROBABILITY, $\bar{P}_b$, JUPITER/SATURN CHANNEL ALONE
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
1
2
3
4
5
6
7
8
E_b/N_0, dB
2.6 dB
44
JUPITER / SATURN CHANNEL
VITERBI DECODED
CONVOLUTIONAL
K=7, V=2
2.6dB
42
CONCATENATED
REED-SOLOMON
(J=8, E=16) &
VITERBI DECODED
CONVOLUTIONAL
K=7, V=2

FIG. 4

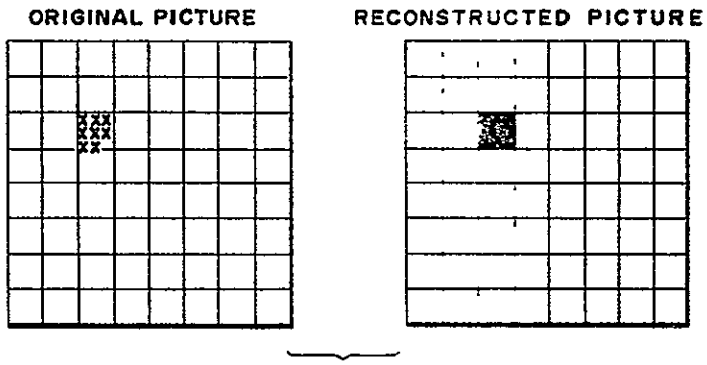


FIG 5

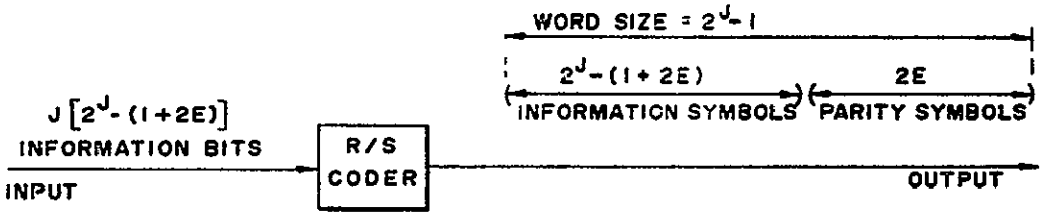


FIG. 6

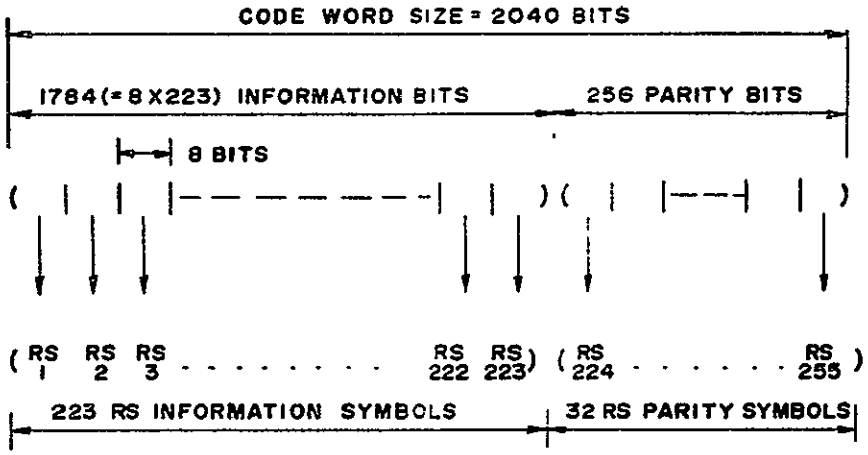
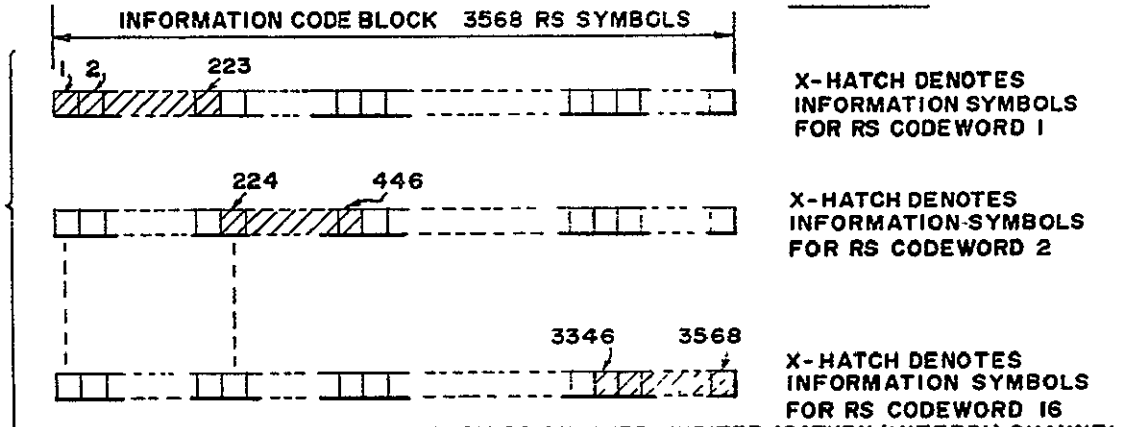
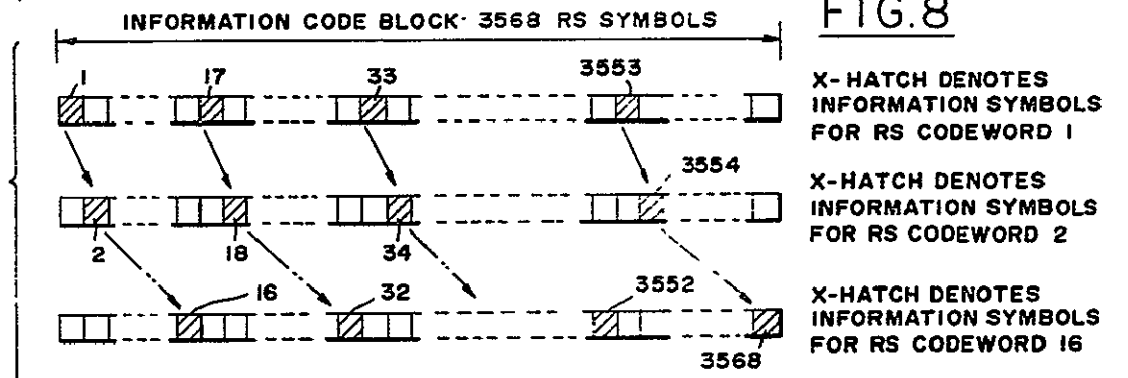


FIG. 7



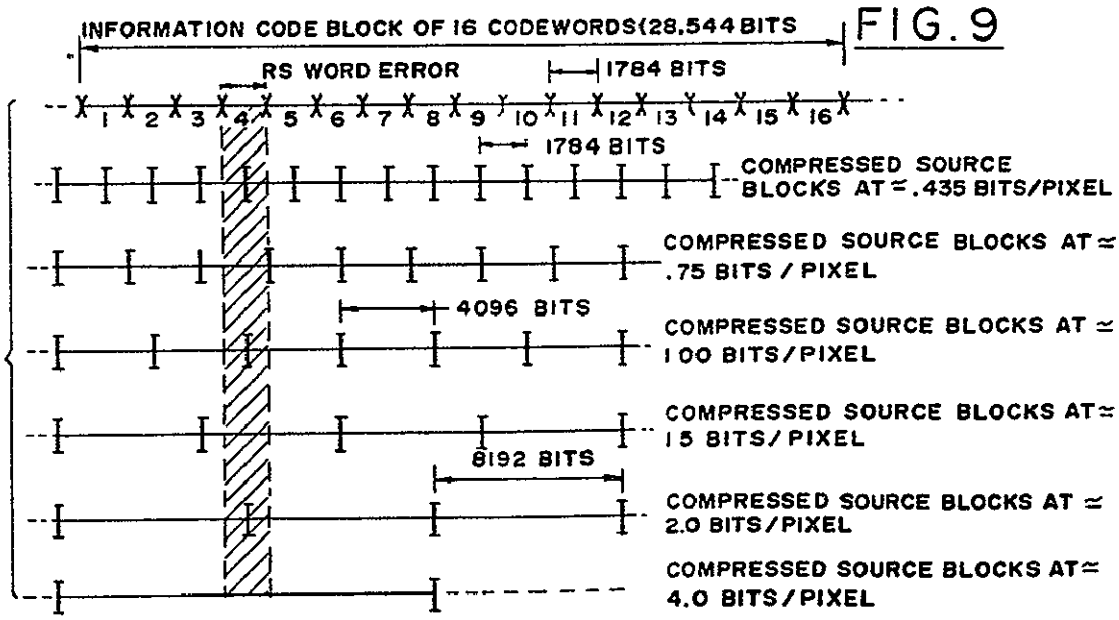
ORDER OF RS INFO SYMBOL TRANSMISSION OVER JUPITER/SATURN (VITERBI) CHANNEL IS (1,224, . . ,3346),(2,225,. ,3347), (223,446, ,3568)
SIMILARLY FOR PARITY SYMBOLS.

FIG. 8



DIAGONAL ARROWS INDICATE THE ORDER OF RS SYMBOL TRANSMISSION OVER THE JUPITER/SATURN (VITERBI) CHANNEL
SIMILARLY FOR PARITY SYMBOLS

FIG. 9



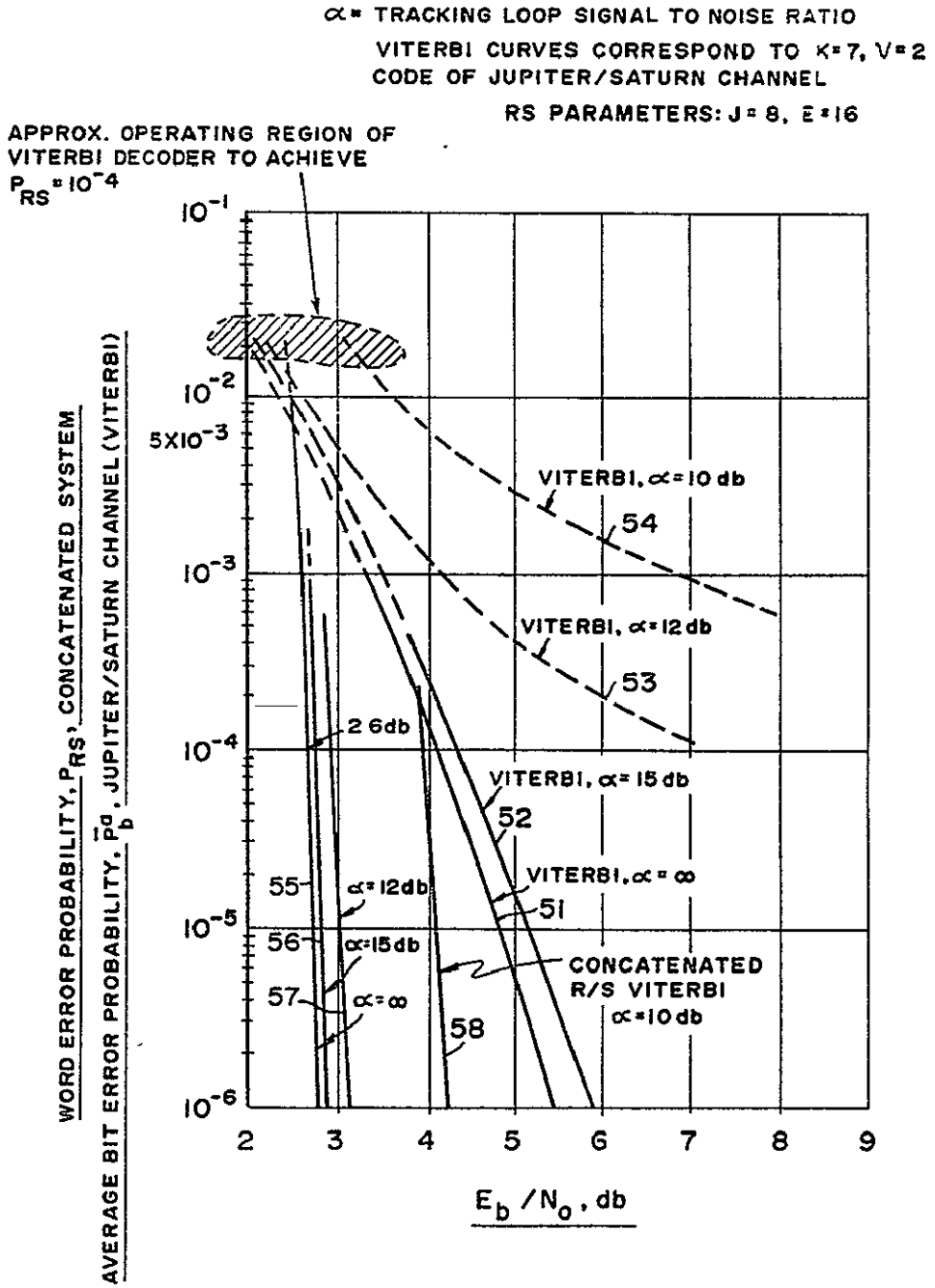

α = TRACKING LOOP SIGNAL TO NOISE RATIO
VITERBI CURVES CORRESPOND TO K=7, V=2
CODE OF JUPITER/SATURN CHANNEL
RS PARAMETERS: J = 8, E = 16
APPROX. OPERATING REGION OF
VITERBI DECODER TO ACHIEVE
$P_{RS} = 10^{-4}$
WORD ERROR PROBABILITY, P_{RS}, CONCATENATED SYSTEM
AVERAGE BIT ERROR PROBABILITY, $\bar{P}_b^a$, JUPITER/SATURN CHANNEL (VITERBI)
10^{-1}
10^{-2}
5×10^{-3}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
VITERBI, α = 10 db
54
VITERBI, α = 12 db
53
2 6db
VITERBI, α = 15 db
52
VITERBI, α = ∞
51
55
α = 12db
56
α = 15db
57
α = ∞
58
CONCATENATED
R/S VITERBI
α = 10 db
2
3
4
5
6
7
8
9
E_b / N_o, db

FIG. 10

ORIGINAL PAGE IS
OF POOR QUALITY

SPACE COMMUNICATION SYSTEM FOR COMPRESSED DATA WITH A CONCATENATED REED-SOLOMON-VITERBI CODING CHANNEL

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract and is subjected to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 85-568 (72 Stat. 435, 42 USC 2457)

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention generally relates to a communication system and, more particularly, to an improved system for communicating compressed data from a spacecraft to Earth

2 Description of the Prior Art

As is known by those familiar with the art of advanced space communication the information which is gathered in a spacecraft, generally referred to as data, is first coded to be transmitted to Earth, where it is received at one or more ground stations The received coded data is first decoded and thereafter processed to retrieve the original data which is in the form of a stream of bits The coding of the data in the spacecraft and the decoding of it after reception on the ground is generally referred to by the well known term "channel coding" As is appreciated, the basic motivation for channel coding has been to reduce the frequency of errors in the output information bit stream for a given signal to noise ratio, E_b/N_o, or conversely, to increase the transmission rate, R_b, at which information can be transmitted with a given error probability For each channel coding technique the average bit error probability is generally plotted as a function of the signal to noise ratio (in db) These plots are generally referred to as the performance curves

In the last few years many articles have appeared in various publications in which various channel coding techniques are analyzed and their relative merits highlighted The following are but a few of prior art references:

A A J. Viterbi, "Convolutional Codes and their Performance in Communication Systems", IEEE Trans. Commun Technol., Volume COM-19 and part II, October 1971, pp. 751–772

B. J A. Heller and I M Jacobs, "Viterbi Decoding for Satellite and Space Communication", IEEE Trans Commun Technol, Vol COM-19, part II, October 1971, pp 835–848

C J P Odenwalder et al, "Hybrid Coding Systems Study", Final Report prepared by Linkabit Corporation for Ames Research Center NASA, September 1972 This report is available to the public as NASA Cr 114,486

Reference A is an excellent tutorial on a decoder now generally referred to as the Viterbi decoder for use with a convolutional coder and a modulator and transmitter in the spacecraft and a receiver and demodulator on the ground, hereinafter generally referred to as the Viterbi channel Extensive performance characteristics of the Viterbi channel for different constraint lengths, represented by K, and different code rates, represented by $1/\nu$, are analyzed and plotted in reference B Most of the curves in reference B are plotted under assumed ideal operating conditions in which the

carrier phase tracking loop signal-to-noise ratio, represented by α, is assumed to be infinity In FIG 15 on page 845 of reference B the performance of the Viterbi channel for $K=7$ and $\nu=2$, i e, a code rate of ½ for various values of α is plotted in terms of bit error rate vs E_b/N_o (in db) As seen therefrom for any desired bit error rate the required system's E_b/N_o increases (transmission rate drops) as a α becomes smaller

Reference C is related to a hybrid coding system which is analyzed The hybrid system, as shown on page 10 of reference C, includes a Reed-Solomon (RS) encoder which encodes data gathered at a remote location, e g a spacecraft, into RS codewords, each consisting of code symbols and parity symbols. These codewords are first interleaved by means of a buffer prior to being encoded by a convolutional encoder in the spacecraft The received coded data on the ground is first decoded by a Viterbi decoder whose output is loaded into a deinterleaving buffer to reconstruct the RS codewords which are then decoded by a RS decoder The output of the latter is the fully decoded data which is then processed Since the convolutional encoder and the Viterbi decoder along with the modulation and demodulation system have been defined herein as a Viterbi channel, the system described in reference C can be defined as a concatenated RS-Viterbi channel, or system hereinafter it may also be referred to by the simpler term "the concatenated system".

Although in reference C the advantages of the concatenated RS-Viterbi channel over other known channels are discussed, it should be stressed that in reference C the performance of the concatenated RS-Viterbi channel are analyzed only under assumed ideal conditions, i e, $\alpha = \infty$ Performance under non-ideal conditions are neither discussed nor suggested Also, none of the above mentioned references consider the channel from a system's point of view, including the type of data which is to be communicated

As is appreciated by those familiar with the art of information communications, it is generally desirable to reduce the number of bits which represent any information e g, a picture of a planet, and which have to be transmitted without significantly sacrificing information content This is desirable, since by reducing the number of bits, more information can be transmitted to Earth during any given period of time This can be achieved if the original data, gathered in the spacecraft, can be compressed to reduce the number of bits needed to communicate the information before any coding is performed As is appreciated various compression techniques may be employed Then, after the data is decoded on the ground it can be decompressed, based on the particular compression technique employed in the spacecraft, to provide non-compressed data which is finally processed It is appreciated however that when communicating compressed data a much lower average bit error rate is generally required as compared with non-compressed data since a single error in the compressed data stream is often propagated by the data decompressor into many errors in the reconstructed data

OBJECTS AND SUMMARY OF THE INVENTION

It is a primary object of the present invention to provide a new communication system for communicating data from a spacecraft to Earth

Another object of the present invention is to provide a new spacecraft communication system for communi-

Reproduced from best available copy.

ORIGINAL PAGE IS
OF POOR QUALITY

cating compressed data at an acceptable bit error probability.

These and other objects of the invention are achieved by providing a communication system in which a concatenated RS Viterbi channel is employed and through which compressed data is communicated The invention will first be described in connection with communicating compressed image data, although the invention is not intended to be limited thereto The invention is based on an analysis indicating that by proper choice of the depth of interleaving of the RS codewords and due to the properties of the Viterbi channel compressed image data can be communicated through the concatenated RS-Viterbi channel at a sufficiently low RS codeword error probability, even under non-ideal conditions, i e , when $\alpha \neq \infty$, at a system signal-to-noise ratio E_b/N_o which is on the order of the E_b/N_o needed for communicating via a Viterbi channel alone non-compressed image data at an acceptable bit error probability This arrangement is possible since the analysis indicates that, unlike the Viterbi channel in which for relatively low average bit error probability on the order of 10^{-4} the system's E_b/N_o increases greatly as α decreases, in the concatenated RS-Viterbi channel by proper choice of parameters, including RS codeword interleaving depth, the change in E_bN_o for low codeword error probability changes only by a small factor as α decreases

The novel features of the invention are set forth with particularity in the appended claims. The invention will best be understood from the following description when read in conjunction with the accompanying drawings

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a general block diagram of the novel communication system of the present invention,

FIG 2 is a simplified diagram of an original and reconstructed picture used to indicate the effect of source block losses due to random errors,

FIG 3 is a diagram of performance curves for a Viterbi channel and the concatenated system under ideal conditions;

FIG. 4 is a diagram similar to FIG 2 except that all errors are assumed to be concentrated in one source block,

FIG 5 is a simple diagram useful in explaining the operation of a RS coder;

FIG. 6 is a basic RD codeword structure for J=8, E=16,

FIGS 7 and 8 are useful in explaining two different interleave structures for interleaving I=16 RS codewords,

FIG 9 is a diagram useful in explaining the effect of a RS codeword error using interleave A shown in FIG 7; and

FIG 10 is a diagram of performance curves of a Viterbi channel and the concatenated RS-Viterbi channel under ideal and non-ideal conditions

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Attention is first directed to FIG 1 wherein numeral 10 designates a source of data in a spacecraft, the data being in the form of a stream of bits The data from source 10 is supplied to a data compressor 12 whose function is to compress the data in accordance with preselected compression criteria, so as to reduce the number of bits as compared with those supplied thereto from source 10.

For explanatory purposes, let it be assumed that a picture was taken of a planet and that the picture consists of an array of 512 by 512 picture elements, hereinafter defined as pixels and that each group of 64 by 64 pixels represents a source block, with the entire picture being represented by 64 source blocks It is further assumed that for each pixel data source 10 provides a stream of eight bits Let the number of bits of an uncompressed source block defined as R_{pcm}^B (which in the particular example is 64 × 64 × 8) and after compression the number of bits for each source block be defined as R_c^B Thus, compression factor, provided by compressor 12, may be defined as $CF = R_{pcm}^B/R_c^B$ Clearly, the principal motivation for data compression is, of course, to obtain compression factors (CF) greater than 1 Various schemes have been proposed for data compression and since the present invention is not directed to a specific scheme, the data compressor 12 will be shown only in block form

The compressed data from 12 is supplied to a Reed-Solomon (RS) coder and interleaver 14. For explanatory purposes it is assumed that J=8, representing the number of bits per RS symbol, E=16, where E is one-half the number of parity symbols per RS codeword or the number of RS symbols which can be corrected and I=16, I being the number of interleaved RS codewords representing an RS block

As is appreciated by those familiar with the art a Reed Solomon code is a BCH code with a specific set of parameters The prior art provides all the background necessary to build an RS coder and interleaver as well as an RS decoder and deinterleaver Therefore in the present application these units or devices will be represented in block form only. The prior art includes at least reference C, chapter 6 of "Information Theory and Reliable Communication" by R G Gallager published in 1968, "Algebraic Coding Theory" by E. R Berlekamp, published in 1968, and an article by James L. Massery, Shift Register Synthesis and BCH Decoding", IEEE Trans Info Theory, vol IT-15, pp 122–127, January 1969 There are other publications known to those familiar with the art

The compressed data from 12 after being RS coded into codewords which are interleaved to form an RS code block are in turn coded by a convolutional encoder 16, assumed to have a constraint length K=7 and a code rate of ½, i e , ν=2 The output of the latter is then transmitted to Earth through a modulator/transmitter 17, hereinafter also referred to as transmitter 17, which includes a transmitting antenna 18. The transmitted signals are represented by arrow 19. Herein it is assumed that in modulator/transmitter 17 antipodal PSK-PM modulation of a square wave subcarrier with S-band or X-band carrier takes place.

On Earth several deep space network stations designated DSN1-DSNn are located at different locations to insure that at any time the signals 19 from the spacecraft are received at at least one of the DSN's These stations are identical The signals received on Earth are designated by numeral 20. Each DSN includes a receiver antenna 21 connected to receiver/demodulator 22, hereinafter simply referred to as the receiver 22, which is assumed to include a phase locked loop coherent demodulator with a three-bit quantized symbol output Herein, it is assumed that the signals from the spacecraft to Earth are subject to wideband Gaussian

Reproduced from best available copy.

ORIGINAL PAGE IS
OF POOR QUALITY

noise. That is, the communication channel including the transmitting and receiving antennas as well as the environment through which the signals propagate between is a wideband Gaussian channel.

In accordance with the present invention, each DSN also includes a Viterbi decoder 24 which is designed to respond to the receiver/demodulator output and attempts to reproduce the original data stream entering the convolutional encoder 16 in the spacecraft

As hereinbefore defined the Viterbi decoder 24 together with the encoder 16 and the modulator/transmitter 17 and the receiver/demodulator 22 together with the wide band Gaussian noise channel (between the spacecraft and Earth) represent a Viterbi channel With $K=7$ and $\nu=2$, the Viterbi channel is sometimes referred to as the Jupiter/Saturn channel by those involved in constructing a communication channel for a spacecraft to be used in missions planned for the late 1970's to explore Jupiter and Saturn. Viterbi decoders with different K and ν are presently available as off the shelf items One source is Linkabit Corporation of San Diego, Calif, whose literature extensively describes such channels Modulator/transmitters, like 17 and receiver/demodulators like 22 as hereinbefore defined as well known by those familiar with the art of communication, particularly as related to space communication Such modulator/transmitters and receiver/demodulators have been used in prior space missions and are described in literature

The output of the Viterbi decoder 24 (of each DSN) is directly supplied to a single RS decoder and deinterleaver 25, hereinafter simply referred to as the RS decoder 25. Its function is to decode the Viterbi decoder output by separating the received 16 (when $I=16$) interleaved RS codewords into separate RS codewords and thereafter decode these words The output of RS decoder 25 in essence represents the compressed data which data compressor 12 supplied to the RS coder 14 in the spacecraft The compressed data from RS decoder 25 is then supplied to a data decompressor 27 which effectively reconstructs from the compressed data an approximation to the original noncompressed data, provided in the spacecraft by data source 10 to data compressor 12. The reconstructed non-compressed data from decompressor 27 is supplied to a data processor 29 for processing, e g., produce an approximation of the original picture. except for any lost source blocks due to errors in the transmission The RS decoder 25, the data decompressor 27 and the data processor 29, are located at a central data processing center 30, such as the one presently existing for processing data received from prior space missions

It should be appreciated that the arrangement shown in FIG 1 is a concatenated RS-Viterbi channel or system for communicating compressed data from a spacecraft. It is conceded that such a channel is discussed in reference C However, therein the channel was only analyzed under ideal conditions ($\alpha=\infty$). Also in reference C no consideration was given to the usefulness of the channel to transmit compressed data under any conditions

The great advantage of the channel to transmit compressed data will become apparent from the following discussion on which the invention is based The discussion may be facilitated by considering compressed image data. As hereinbefore suggested let it be assumed that the data source 10 is one providing a stream of bits representing an original picture, as shown in FIG 2. Let it be assumed that the picture consists of 512 by 512 picture elements or pixels, and each pixel from source 10 is represented by eight bits (for 256 grey level quantization) Let it further be assumed that the data compressor 12 compresses the data into source blocks, each consisting of a two dimensional array of 64 by 64 pixels.

These source blocks are made independent by preceding the bits representing each source block with a sufficiently long sync word Each sync word is used to identify the start of the following source block By choosing a sufficiently large source block (in terms of the number of bits) the sync word has negligible effect on the transmission rate In FIG. 2, the smaller squares represent the separate source blocks In FIG 2 a small x in a source block means that after reception the corresponding source block has an error somewhere in it It is assumed that a bit error in any source block, regardless of where the error occurs within a compressed source block, the block is completely lost, since a single error in the compressed data stream is often propagated by the data decompressor into many errors in the decompressed data The above assumption is a worst case assumption and therefore includes any data compression process which may be used

A key point in this example is that because the location of bit errors was generally uniformly distributed throughout the compressed data, each error appeared in a different compressed source block Consequently, each error caused the loss of a different source block. If such compressed data were to be transmitted through a Jupiter/Saturn channel (a Viterbi channel with $K=7$ and $\nu=2$) extremely low average bit error rates $\overline{P_b}$ on the order of 10^{-6} and 10^{-7} will be required. And, even then the errors will tend to occur in approximately this random fashion

Reference is now made to FIG 3 in which the Jupiter/Saturn channel performance curve is shown, under assumed ideal conditions, i e , $\alpha=\infty$ It is designated by numeral 42. As is known to those familiar with the art for uncompressed image data, hereinafter referred to as uncompressed PCM, average bit errors probability $\overline{P_b}$ below 5×10^{-3} is regarded as negligible Thus, the Jupiter/Saturn channel can operate as a signal-to-noise ratio, $E_b/N_o \approx 2.6$ db. However, to obtain average bit error bit probability on the order of 10^{-6} for compressed data the required increase in E_b/N_o is about 3 db higher which corresponds to a reduction in transmission rate by a factor of about two under only ideal conditions Thus, a net gain cannot be obtained from the data compression and the Jupiter/Saturn channel unless the average compression factor (CF) exceeds approximately two However, under practical operating conditions, as will be described hereinafter, in which $\alpha \neq \infty$ much higher E_b/N_o is required to obtain very low bit error probability on the order of 10^{-6} Furthermore, in the Jupiter/Saturn channel with relatively low values of α, bit error probability on the order of 10^{-6} or less is not even obtainable, except with extremely large E_b/N_o. This will become apparent from the discussion in connection with FIG. 10.

The reason that the Jupiter/Saturn channel is not efficient for data compression communication is due to the fact that its performance curve is not steep enough. That is, to lower $\overline{P_b}$ from 5×10^{-3} to about 10^{-6} requires a large increase in E_b/N_o Another important point is the general random distribution of individual

Reproduced from best available copy.

ORIGINAL PAGE IS
OF POOR QUALITY

bit errors in the Jupiter/Saturn channel at low $\overline{P_b}$ values on the order of 10^{-6}. Consequently, if the Jupiter/Saturn channel were used, due to the random distribution of the individual bit errors, the reconstructed picture would look as shown in FIG. 2 with the black source blocks being lost blocks, which in most cases would be unacceptable If should thus be appreciated that one desired property of the channel is that for a given average error probability, the errors occur in bursts For example, if as shown in FIG. 4, which is similar to FIG 2, the eight errors were to occur in one source block since the first error in the compressed source block causes all the damage, the other seven errors are of no consequence and therefore in the reconstructed picture the eight errors will only cause the loss of a single source block

The proposed solution to this problem is provided by the insertion of the RS coder 14 in the spacecraft and the RS decoder 25 on the ground A key to the simplicity of this configuration is that the RS decoder need not be inserted in each DSN station and only one such decoder 25 is needed at the central data processing center 30. The RS encoder 14 can be considered together with the data compressor 12 as the source encoding unit, and the RS decoder 25 as part of the data processing center, with the communication channel being the Jupiter/Saturn channel (Viterbi channel with $K=7$, $\nu=2$) However, to demonstrate that the addition of the RS coding and decoding offers a solution for the communication of compressed data the purpose is better served by regarding the RS coder and decoder as part of the concatenated RS-Viterbi channel or system.

As is appreciated by those familiar with RS coders and as diagrammed in simple form in FIG. 5, let it be assumed that $J[2^J-(1+2E)]$ information bits from a source. such as compressor 12, are received The result of the coding operation is a codeword of 2^J-1 RS symbols of which the first $2^J-(1+2E)$ are RS information symbols, representing the incoming information bits, and the remainder of the codeword is filled with 2E parity symbols An RS symbol (whether information or parity) is in error if any of the J bits making up the symbol are in error. E represents the number of correctable RS symbol errors in an RS codeword. That is, if E or less RS symbols in a codeword are in error in any way, the RS decoder will be capable of correcting them FIG. 6 is a diagram of the basic RS codeword structure for $J=8$, $E=16$, formed for a stream of 1784 information bits entering the RS coder 14.

To make the most effective use of the power of RS coding when concatenated with Viterbi decoded convolutional codes requires interleaving This is because of the burstiness in error events experienced by Viterbi decoders at values of E_b/N_o of interest (between 2 0 and 2 5 db) Without interleaving Viterbi decoder burst error events would tend to occur within one RS codeword That one codeword would have to correct all of these errors Thus, over a period of time there would be a tendency for some codewords to have "too many" errors to correct (i e, greater than 16, when $E=16$) while the remaining codewords would have "too few" (i e, much less than 16). This situation does not make effective use of the capabilities of the RS coding The effect of interleaving is to spread these bursty error events over many codewords so that the RS decoder tends to work uniformly hard on all the data

Two methods of interleaving will be investigated here We will call them Interleave A and Interleave B The first exhibits a slight performance advantage in the transmission of compressed data whereas the second offers an advantage in memory requirements for the onboard RS coder 14. In both cases we will assume an interleaver depth, $I=16$

INTERLEAVE A

A diagram illustrating Interleave A is shown in FIG 7. The consecutive numbers 1, 2 . . . , 3568 denote labeling of consecutive RS information symbols which are to be interleaved and coded into 16 RS codewords These symbols correspond to the compressed data grouped into eight bit symbols) as it would enter the RS coder 14 from data compressor 12. We call this sequence of bits an Information Code Block to distinguish it from a Code Block which also includes parity symbols The length of an Information Code Block is (16) (223) = 3,568 RS symbols or (8) (3568) = 28,544 bits

The crosshatched regions specify which RS information symbols belong to each of the 16 codewords As specified, the first 223 form the information symbols of codeword 1, the second 223 information symbols belong to codeword 2, and so on Without interleaving these symbols along with their 32 parity symbols, would be transmitted over the Jupiter/Saturn channel in the order in which they appear Thus a particularly long burst of errors from the Viterbi decoder would tend to affect the symbols of only one codeword With Interleave A the order of RS information symbol transmission is (1, 224, . . . , 3346), (2, 225, . . . , 3347), . . (223, 446, . . . , 3568). That is, the first symbol from codeword 1, the first symbol from codeword 2, . . . , the first symbol from codeword 16, the second symbol from codeword 1, and so on The parity symbols would follow in the same manner. With this arrangement it should be clear that a burst of errors that spans $k \leq 16$ RS symbols (128 bits) will be distributed among k different codewords.

Since the information symbol 3346 in the 16th symbol to be transmitted, memory for the complete Information Code Block must be provided in addition to that required for parity symbol generation However, with present day technology this much working memory today is really insignificant For example, Advanced Pioneer mission planners are presently assuming at least 10^6 bits of working memory. Single solid state chips are available off the shelf with 4096 bits of random access memory. However, we point out that the second interleave method, Interleave B, does offer an advantage in this area by requiring memory only for the parity symbols

If 16 or less RS symbols of a codeword are in error before entering the RS decoder, then all information symbols of that codeword leaving the decoder will be correct No decoding error is made On the other hand, if more than 16 RS symbols of a particular codeword are in error before decoding, then a decoding error will occur and the output information symbols may have many errors If we interpret FIG. 7 as describing an output Information Code Block we see that the effect of a decoding error on a particular codeword is constrained to the corresponding crosshatched region for that codeword Thus, for Interleave A the effect of an RS decoding error is confined to consecutive symbols An RS decoding error will appear as a burst of errors of up to 223 symbols in length (1784 bits). Earlier we pointed out that this bursty property is desirable for the

Reproduced from best available copy.

ORIGINAL PAGE IS
OF POOR QUALITY

transmission of compressed data. We will see that it is the relatively greater burstiness of Interleave A over Interleave B that gives Interleave A a slight performance advantage.

INTERLEAVE B

Before investigating the specific effects of RS codeword errors on compressed data, we need to establish the basic structure of Interleave B. This is shown in FIG. 8. Again the consecutive numbers 1, 2, . . . , 3568 denote the labeling of consecutive information symbols. Also as in FIG. 7, the crosshatched regions specify which information symbols belong to each of the 16 codewords. Note that for each codeword, adjacent symbols are separated by 15 other symbols in the Information Code Block. For example the information symbols for codeword 1 are made up of Information Code Block Symbols 1, 17, 33, . . . , 3553. As indicated by the arrows, the order of transmission of RS information symbols (over the Jupiter/Saturn channel) is exactly the same way they appear in the Information Code Block 1, 2, . . . , 16, 17, . . . , 3568. Parity symbols would follow in the same manner. It is easy to see that this accomplishes the desired interleaving (e.g., a burst error event from a Viterbi decoder would have to span symbols 2 through 16 in order to affect adjacent symbols 1 and 17, of codeword 1). In addition this ordering means that no memory is required for the Complete Information Code Block, since this data can be transmitted, unchanged as it arrives from data compressor 12. Thus, significantly less memory is required for this form of interleaving.

Just as we did in FIG. 7 we can interpret FIG. 8 as describing an output Information Code Block so that, as before, the effect of a decoding error on a particular codeword is specified by the crosshatched regions for that codeword. Unlike Interleave A, we note that these crosshatched regions are spread throughout the Information Code Block rather than constrained to a consecutive string of 223 symbols. The consequences of this spread-out will be seen later.

The choice of interleaver $I=16$ was selected to achieve statistical independence between RS symbols of individual codewords before decoding. That an interleaver depth of 16 is sufficient to make any dependencies negligible for our specific concatenated coding system is highly plausible. Error bursts from a Viterbi decoder exceeding 120 bits (16 RS symbols) are extremely unlikely for the $K=7$, $r=\frac{1}{2}$ code for E_b/N_o values as low as 1.4 db ($<10^{-5}$). It was primarily such observations which led to choose $I=16$ along with the fact that 16 is a power of 2. This choice would seem to even be overdoing it for the specific code of the Jupiter/Saturn channel, particularly under nominal phase coherent receiver conditions (for which our interests will be restricted to Viterbi decoder E_b/N_o values greater than about 2 db). Perhaps the major point to keep in mind is that even doubling interleaver depth to 32 does not severely impact the implementation of either coder or decoder.

We will continue with the assumption that enough interleaving is provided to make the assumption of independent RS symbol error events a valid one. An interleaver depth of no more than $I=16$ should be completely adequate in this sense. From a more practical point of view $I=16$ may not be necessary. If desired $I=8$ may be chosen.

With π denoting the average probability of an RS symbol error leaving the Viterbi decoder (group of eight bits), the probability of an RS codeword error (using Interleave A or B) is given by

$$P_{RS} = Pr\begin{bmatrix}\text{more than 16}\\ \text{independent symbol}\\ \text{errors}\end{bmatrix} \tag{1}$$

$$= \sum_{k=17}^{255} \binom{255}{k} \pi^k (1-\pi)^{255-k}$$

Thus P_{RS} is determined entirely by π. The term π can be determined by directly monitoring the correctness or incorrectness of RS symbols emanating from simulated Viterbi decoders at various signals to noise ratios, or from Viterbi burst error statistics to obtain the same results. A performance curve (P_{RS} vs E_b/N_o) which was derived from Equation (1) and the experiments which produced the various values of π is shown in FIG. 3, under which ideal conditions ($\alpha=\infty$) are assumed.

The effect of a codeword error on compressed data in the form of source blocks will now be discussed using the above referred to example for source blocks. That is, attention is restricted to source blocks originating from 4096 pixels (e.g., 64 by 64 pixel arrays). Hereinbefore R_c^B was defined as the number of bits of compressed data representing a source blocks, and R_{pcm}^B the number of bits of 4096 pixels representing a source block without compression. With eight bits/pixel $R_{pcm}^B = 8 \times 4096$. However, the number of bits of a compressed source block, i.e., R_c^B clearly depends on the compression factor, CF.

FIG. 9 illustrates the effect of an individual RS codeword error on sequences of compressed source blocks when Interleave A is employed. At the top of the figure is shown an output Information Code Block in much the same manner as in FIG. 7. The subsequences of decoded information bits for each of the 16 codewords are indicated by the parentheses and are labeled from 1 to 16. Each subsequence is 1784 bits long for a total of 28,544 bits. The number of compressed source blocks making up the 28,544 bits depends on the distribution of compressed source block rates, R_c^B. That is, how many bits it takes to represent each compressed source block. We will look at the simpler case in which each compressed source block in the sequence is represented by a fixed number of bits.

Shown immediately below the Information Code Block in FIG. 9 is a sequence of compressed source blocks which each require 1784 bits. This is equivalent to about 0.435 bits/pixel (CF=20) assuming 4096 pixel source blocks. Each compressed source block is indicated by brackets. Note that the start of the first RS codeword is not (necessarily) synchronous with the start of a compressed source block. Thus, the Information Code Block contains data from 17 compressed source blocks.

Below this example are shown several similar illustrations for increasing compressed source block rates (lower compression factors) starting with average rates of 0.75 bits/pixel and increasing up to 4.0 bits/pixel. Note that because of the increasing number of bits to represent a compressed source block the Information Code Block represents fewer and fewer source blocks. At four bits/pixel a compressed source block is over 16,000 bits long so that an RS Information Code Block

Reproduced from best available copy.

ORIGINAL PAGE IS
OF POOR QUALITY

only "overlaps" two or three compressed source blocks

To investigate the effect of an RS codeword error, we restate some earlier results and assumptions First we assume that if any error occurs in a compressed source block, that complete source block is lost but no more We add to this by assuming that if an RS codeword is in error after decoding, all decoded information bits are in error for that codeword Finally we recall from FIG 7 that when Interleave A is used, the effect of a codeword error is constrained to a consecutive sequence of information bits (symbols) In FIG 9 these potential error sequences are those enclosed by parentheses and labeled 1 to 16 In FIG 9 it is assumed that codeword 4 was in error By our assumptions above, any compressed source block which is represented by this sequence of wrong bits is lost In FIG 9 this corresponds to any compressed source block which falls in the crosshatched region In all cases we observe the following, using Interleave A the number of source blocks lost due to an RS codeword error is 1 or 2

To obtain similar results for Interleave B, we recall from FIG 8 that when a single RS codeword errors occurs the effect is spread uniformly across the complete Information Code Block Thus the typical number of lost source blocks in simply the number of compressed source blocks represented by the Information Code Block Extending our earlier observations using FIG. 9 results in a summary comparison of Interleave A and B in Table 1

Table 1

Comparison of Interleave Methods

Rate of Compressed Source Block in Bits	Rate in Bits/Pixel	Error Event: Typical No of Lost Source Blocks due to RS Word Error — Interleave A	Interleave B
1,784	≈0 435	1 or 2	15 or 16
4 096	1 0	1 or 2	9 or 10
8 192	2 0	1 or 2	5 or 6
16,384	4 0	1 or 2	2 or 3

*Source block contains 4096 pixels.

The discussions just completed describe the effect of individual RS codeword errors in terms of lost source blocks The next question to address is the determination of the largest value of P_{RS} for which the overall impact of these error events is considered negligible More simply, how often can we let these error events occur

With an RS codeword error rate given by P_{RS}, on the average, a source block error event would occur every $1/P_{RS}$ RS codewords

But the number of source blocks per RS codeword is given by

$$\gamma = (1784 \text{ information bits/RS word})/(R_c^2 \text{ bits/source blocks}) \quad (2)$$

Thus, on the average a source block error even would occur every

$$N_{SB} = \gamma/P_{RS} \text{ source blocks} \quad (3)$$

To carry this point further to a situation which is more readily visualized, assume that our 4096 pixel source blocks are 64 by 64 pixel arrays Further, assume that the frame size for a picture is 512 by 512 pixels making up a total of 64 source blocks as in the example of FIG 2. Using equation 3 we can then say that, on the average, a source block error event would occur every

$$N_p = (N_{SB})/(64) \text{ pictures} \quad (4)$$

Equation 4 is evaluated for three values of P_{RS} in Table 2

Table 2

Number of Pictures Between Source Block Errors

Source Block Rates in Bits/Pixel	N_p(Eq 4) = Average Number of Pictures Between Source Block Error Events (see Table 1): $P_{RS} = 10^{-3}$	$P_{RS} = 2 \times 10^{-4}$	$P_{RS} = 10^{-4}$
≈0 435	13 6	68	136
1 0	6 8	34	68
2 0	3 4	17	34
4 0	1 7	8 5	17

*Source Block contains 4096 pixels
**Picture Size 512 by 512 pixels (64 source blocks)
***P_{RS} = Probability of an RS codeword error

From Table 2 it is seen that with the choice of $P_{RS} = 10^{-4}$ and a source block rate of 4 bits/pixel, typically only 1 out of 17 pictures would have any degradation due to the channel That is, the quality of 16 out of 17 pictures would be controlled solely by the characteristics of the particular data compression operation Typically, every 17th picture would suffer the loss of one or two source blocks with Interleave A or two or three source blocks with Interleave B

Decreasing the source block rate (increasing the compression factor) lengthens the interval between source block error events Specifically, with $P_{RS} = 10^{-4}$ and a source block rate of 0 435 bits/pixel, we see that typically only 1 out of 136 pictures would have any loss in quality associated with the channel. Every 136th picture or so would suffer the loss of one or two source blocks if Interleave A were used or 16 to 17 source blocks if Interleave B were used (see Table 1).

From the performance curve of the concatenated RS-Viterbi system, shown in FIG 3 and designated by 44, it is seen that for $P_{RS} = 10^{-4}$ the signal-to-noise ratio E_b/N_o is on the order of 2 6 db Due to the steepness of the curve, changing P_{RS} by an order of magnitude requires only a change in E_b/N_o of about 0 1 db. Thus, the selection of the highest acceptable value of P_{RS} as the value of RS codeword error probability, below which the effect of lost source blocks can be considered negligible for both interleave methods is not critical For purposes of discussion $P_{RS} = 10^{-4}$ is selected as the highest acceptable value

Before comparing the two performance curves, shown in FIG 3, attention is given to the use of the channel to transmit uncompressed data, generally referred to as uncompressed PCM When an RS codeword error occurs during the transmission of uncompressed PCM, the result is a burst of errors extending over 1784 bits using Interleave A or spread more thinly over 28,544 bits using Interleave B. If we assumed eight bits/pixel for each PCM sample, then these error bursts would occur typically once every eight pictures or so If $P_{RS} = 10^{-4}$ Any imagined advantage to accepting a higher frequency of these error bursts in order to increase transmission rate should be tempered by the fact that changing P_{RS} by an order of magnitude requires only 0.1 db Consequently, the insignificant increase in transmission rate will result in error bursts occuring

Reproduced from best available copy.

ORIGINAL PAGE IS
OF POOR QUALITY

more frequently For example, increasing P_{RS} to 10^{-3} would result in an error burst which would occur once in every picture Therefore, $P_{RS} = 10^{-4}$ is also chosen as the maximum RS codeword error probability below which degradation to uncompressed PCM data can be considered negligible

Attention is again directed to FIG 3 in which the performance curves for the Jupiter/Saturn channel (Viterbi channel with $K=7$, $\nu=2$) and the concatenated RS-Viterbi system (with $J=8$, $E=16$, $K=7$, $\mu=2$) are diagrammed It should be recalled that for uncompressed PCM data, transmitted over the Jupiter/Saturn channel, $\overline{P_b} = 5 \times 10^{-3}$ is the approximate value of average bit error probability below which the effect due to errors can be considered negligible This corresponds to an E_b/N_o of 2 6db Similarly, as previously assumed for both compressed or uncompressed data transmitted on the concatenated RS-Viterbi channel $P_{RS} = 10^{-4}$ is a reasonable choice of RS codeword error probability below which any effects due to the channel can be considered negligible This also corresponds to an E_bN_o of approximately 2.6db Thus, it should be appreciated that uncompressed data on the Jupiter/-Saturn channel and both compressed and uncompressed on the concatenated RS-Viterbi channel can be transmitted at about the same rate with negligible degradation due to channel errors It should be pointed out that hereinbefore worst case assumptions for the error sensitivity of compressed data were made Namely, it was assumed that any (one or more) source blocks contained in any RS codeword in error cannot be corrected and that all compressed data contained in such source blocks is lost Therefore, the above statement that for compressed data, transmitted on the concatenated channel, $P_{RS} = 10^{-4}$ is a reasonable choice of RS word error probability below which any effects due to the channel can be considered negligible, applies to virtually any data compression technique.

From the foregoing, it is thus seen that in accordance with the present invention the concatenated RS-Viterbi channel is used to communicate compressed data without having to give up significant transmission rate as compared with the transmission rate required to transmit uncompressed data with the Jupiter/Saturn channel alone The ability to transmit compressed data with the concatenated RS-Viterbi channel without sacrifice of transmission rate has not been realized nor discussed by any of the prior art references

It should be appreciated that any scientific mission to the planets will include data other than that provided by imaging experiments This includes both general science and engineering measurements Some of this data is considered much more sensitive to channel errors than uncompressed PCM imaging data This imposes difficulties when the Jupiter/Saturn channel is employed, as is proposed for the Jupiter/Saturn missions As we discussed for compressed data, just a few errors can severely degrade a complete block of science data for some experiments. It is quite clear that the transmission of such data over the Jupiter/Saturn channel at a 5×10^{-3} average bit error rate produces totally unacceptable degradation. A "cleaner" channel is required for this data

During cruise operations, when science and engineering data totally monopolize the telecommunications channel, an acceptable but not desirable alternative is provided by simply lowering the transmission rate (increasing E_b/N_o) until the error rate is low enough As seen from FIG 3, decreasing the transmission rate by a factor of two on the Jupiter/Saturn channel will reduce the average bit error rate from 5×10^{-3} to about 10^{-6}, and this is only under assumed ideal conditions ($\alpha = \infty$) However, during a close planetary encounter general science and engineering data must "share" the channel with imaging data Imaging experiments are typically allocated between 80 and 90 percent of the total transmission capability during such encounters Reducing the transmission rate by a factor of two to obtain very low error rate is clearly unacceptable for uncompressed PCM imaging experiments, since they only require bit error rates in the vicinity of 5×10^{-3} The presently proposed solution to this problem for the Jupiter/Saturn Mariner missions is to put additional error protection on the general science and engineering data using a modified Golay block code.

However, from the foregoing discussion and the performance curve of the concatenated RS-Viterbi channel shown in FIG 3, it should be apparent that the concatenated RS-Viterbi channel is ideally suited to the general requirements of science and engineering data This is the case since with the concatenated RS-Viterbi channel very low error rates, needed to transmit general science and engineering data, are attainable without a substantial increase of E_b/N_o With J=8 and E=16 all data can be transmitted through the system at an overall E_b/N_o of 2 6 or 2 7 db with negligible degradation due to errors It should also be noted that it is possible to apply data compression to general science and engineering data without worrying about a disastrous effect from errors Clearly, as seen from FIG 3, by a very small increase in E_b/N_o on the order of about 0 2 db the system can operate with a codeword error probability of 10^{-6} which would satisfy all science and engineering data and be more than enough for the imaging data

As previously pointed out, the performance curves shown in FIG 3 are for assumed ideal conditions in which carrier phase is exactly known, i e., $\alpha = \infty$ However, under actual operating conditions, a phase locked loop, tracking a noisy received signal, will generally provide a phase reference for the demodulator which is imperfect, i e, $\alpha \neq \infty$ This causes a degradation in system performance. The effect of decreasing α on the Viterbi channel has been analyzed in reference B and is diagrammed therein on page 845, for $K=7$, $\nu=2$ Some of the curves from reference B are shown in FIG. 10 for the Viterbi channel for $\alpha = \infty$, $\alpha = 15$db, $\alpha = 12$db and $\alpha = 10$db These curves are designated by numerals 51–54, respectively. It has been appreciated and as seen from FIG 10 in the Viterbi channel as α decreases to obtain a low bit error probability, higher and higher E_b/N_o is required For example, for a bit error probability of 10^{-4} a change in α from 15db to 12db requires a change from about E_b/N_o of 4 4db to about 8db, which corresponds to a reduction in transmission rate by about a factor of 2

The effect of decreasing α on the concatenated RS-Viterbi system has never been analyzed in the prior art. From a first impression it would seem that a similar effect would occur in the concatenated RS-Viterbi system That is, at low codeword error probability on the order of 10^{-4} the needed E_b/N_o would increase greatly from that required for $\alpha = \infty$ as α decreases, in a relationship proportional to that experienced in the Viterbi channel alone. That is, from a first impression one would assume that for a codeword error probabil-

Reproduced from best available copy.

ORIGINAL PAGE IS OF POOR QUALITY

ity on the order of 10^{-4} as α changes from ∞ to lower values, e g., 15db or 12db the required E_b/N_o would increase by about 4db, which would reduce transmission rate by a large factor. It is reasonable to assume that based on such first impression the use of the concatenated RS-Viterbi system was never considered by others for the transmission of compressed data. However, a careful analysis shows that this is not the case That is, the analysis shows that in the concatenated RS-Viterbi channel the increase in E_b/N_o due to a reduction in α from ∞ to reasonable values is quite small for codeword error probabilities of interest.

With a conventional code of K=7, ν=2 in order to obtain a codeword error probability $P_{RS} = 10^{-4}$ the Viterbi decoder operates in the region where its average bit error probability $\overline{P_b}$ is on the order of 1/50. In this region of operation the change in required system's E_b/N_o is very small due to changes of α. For example the change in E_b/N_o from $\alpha = \infty$ to α = 15db in the Viterbi channel at $\overline{P_b} = 1/50$ is on the order of about 0 1db It is by this amount that the performance curve for the concatenated RS-Viterbi system is shifted at $P_{RS} = 10^{-4}$ when α changes from ∞ to 15db. In FIG. **10** the performance curves of the concatenated system for different values of α are designated by lines **55–58**. In the operating region of the Viterbi decoder ($\overline{P_b} = 1/50$) fo a change of α from ∞ to 10db the E_b/N_o difference is about 1 2db Thus, for the concatenated RS-Viterbi system at $P_{RS} = 10^{-4}$ the shift would be from 2.6db to 3 8db However, for a change in α from ∞ to 12db in the concatenated RS-Viterbi system for $P_{RS} = 10^{-4}$ the increase in E_b/N_o is only about 0.3 (from 2 6db to about 2 9db)

For these curves the points for $P_{RS} = 10^{-4}$ for different values of α were calculated based on the shift in the Viterbi curves in the approximate operating region of about 1 50 for the Viterbi decoder bit error rate $\overline{P_b}$, needed to produce a codeword error probability of 10^{-4} The rest of the curves **55–58** were interpolated As seen from FIG **10** the Viterbi curves are practically parallel from about $\overline{P_b}$ of 8×10^{-3} and up Thus, the curves **55–58** are reasonably accurate down to at least a codeword error probability of $P_{RS} = 10^{-6}$.

It should be pointed out that at much lower codeword error probabilities for which the Viterbi decoder operating region is at a bit error probability $\overline{P_b}$, where the Viterbi curves ae no longer parallel, e.g., $\overline{P_b} = 10^{-3}$, the performance curves for the concatenated RS-Viterbi systems would also tend to fan out and would no longer be parallel. However, such low codeword error probabilities are not required for the transmission of compressed data, either image data or data derived from general engineering or scientific experiments. Thus, in the regions of interest for the present invention the performance curves of the concatenated RS-Viterbi system are reasonably assumed to be parallel as shown in FIG. **10**. more importantly, it is seen that at the region of interest, namely $P_{RS} = 10^{-4}$, the difference in required E_b/N_o from ideal conditions ($\alpha = \infty$) to non-ideal conditions, such as α = 12db is very small, e g , 0.3db. Furthermore, it is seen that the performance curves are quite steep and therefore a change in P_{RS} by an order of magnitude requires a minimal change on the order of 0.1db in E_b/N_o

Hereinbefore $P_{RS} = 10^{-4}$ was assumed as the value of RS codeword error probability below which the effect of lost source blocks can be considered negligible. Clearly, if $P_{RS} = 10^{-5}$ were chosen the increase in the required E_b/N_o would be about 0.1db from 2.6db to 2 7db for the ideal case ($\alpha = \infty$) or from about 2 9db to about 3db for α = 12db. Recalling the foregoing equations and Table 2, with $P_{RS} = 10^{-5}$ with a source block rate of 4 0 bits pixel only 1 out of every 170 pictures would have any degradation due to the channel

From the foregoing it is thus seen that since the performance curves of the concatenated RS-Viterbi system are steep and parallel even down to very low (10^{-6}) codeword error probabilities, the RS-Viterbi system is particularly suited to transmit compressed imaging data at E_b/N_o values (2 6 – 3.0db) which are on the order of the E_b/N_o required for transmitting non-compressed image data with a bit error probability $\overline{P_b}$ on the order of 5×10^{-3}. Furthermore, the concatenated RS-Viterbi system can be used to transmit scientific and engineering data at sufficiently low error probabilities without requiring additional coding, such as that provided by the Golay coder, as hereinbefore discussed In addition, it should be stressed that if desired, the system can be used to code and transmit non-compressed data

Hereinbefore the concatenated RS-Viterbi system has been described in connection with J=8, E=16, and K=7, ν=2 It should be appreciated that other code parameters can be employed. As is known J defines the number of bits per RS symbol. Since the memory of any modern minicomputer is structured in powers of two, with a byte size of eight-bits the most common, the choice of J=8 seems to be a preferred one for decoding applications An RS code of J=8, E=8 may offer certain advantages over J=8, E=16. The equation for computation load per codeword is dominated by an E^2 term Thus, by reducing E from 16 to 8 higher decoding rates can be achieved As to the convolutional code, it was described in terms of K=7 and ν=2 since this code is expected to be implemented in the Jupiter/Saturn channel for the future Jupiter/Saturn exploration missions However, the invention is not intended to be limited thereto Other convolutional codes may be used such as K=7, ν=3 which offers an improvement between 0.3 and 0 5db over the K=7, ν=2 code, with improvements largest at higher values of $\overline{P_b}$. Conceivably both codes can be onboard the spacecraft in encoder **16** (see FIG 1). When code K=7, ν=3 is used in the concatenated RS-Viterbi system one can expect an improvement of about 0 4 to 0.5db of E_b/N_o at $P_{RS} = 10^{-4}$

Although particular embodiments of the invention have been described and illustrated herein, it is recognized that modifications and variations may readily occur to those skilled in the art and consequently, it is intended that the claims be interpreted to cover such modifications and equivalents.

What is claimed is:

1. In a communication system for communicating data from a first station to a second station, the arrangement comprising

Reed Solomon coding and interleaving means in a first station adapted to receive data and code it into I interleaved Reed Solomon codewords, each codeword containing $2^J - (1 + 2E)$ Reed Solomon information symbols and 2E parity symbols, each symbol being J bits long, I, J and E being integers;

convolutional encoding means in said first station and characterized by a constraint length definable as K and a code rate definable as $1/\nu$, for encoding

Reproduced from best available copy.

ORIGINAL PAGE IS
OF POOR QUALITY

the coded output of said Reed Solomon coding and interleaving means,

transmitter means in said first station for transmitting the output of said convolutional encoding means to a second station,

receiver means at said second station for receiving signals transmitted by said transmitter means,

Viterbi decoding means at said second station, responsive to the output of said receiver means for decoding the receiver means output to provide an output which is related to the output of said Reed Solomon coding and interleaving means supplied in said spacecraft to said convolutional encoding means,

Reed Solomon decoding and deinterleaving means at said second station responsive to the output of said Viterbi decoding means for deinterleaving said I Reed Solomon codewords and for decoding said codewords to provide an output substantially corresponding to the data adapted to be supplied in said first station to said Reed Solomon coding and interleaving means, said J, E, I, K and ν being selected to provide a Reed Solomon codeword error probability, definable as P_{RS}, which is not greater than a preselected value for a preselected system signal-to-noise ratio, definable as E_b/N_o in db;

data means in said first station for gathering data and for providing an output representing said data as a stream of bits,

data compression means in said first station for compressing the data-representing stream of bits from said data means into a stream of bits representing blocks of data, definable as source blocks, the average number of bits representing each source block being less than the number of bits provided by said data means for the corresponding source block,

means in said first station for supplying the bits representing said source blocks from said data compression means to said Reed Solomon decoding and interleaving means; and

data de-compression means at said second station responsive to the output of said Reed Solomon decoding and interleaving means for providing output data which is an approximation of the data supplied to said data compression means prior to it being compressed therein

2. The arrangement as described in claim 1 wherein P_{RS} is not greater than 10^{-4} when E_b/N_o is in the range between 2 and 3db.

3. The arrangement as described in claim 1 wherein $J=8$, $E=16$, $K=7$ and $\nu=3$.

4. The arrangement as described in claim 1 wherein $J=8$, $E=8$, $K=7$ and $\nu=3$

5. The arrangement as described in claim 1 wherein $J=8$, $E=16$, $K=7$, $\nu=2$ and I is less than 16 but not less than 8.

6. The arrangement as described in claim 1 wherein $J=8$, $E=16$, $K=7$ and $\nu=2$.

7. The arrangement as described in claim 6 wherein $I=16$.

8. A method of communicating data from a spacecraft to a data processing center on Earth, the steps comprising:

gathering data in a spacecraft,

compressing the gathered data in said spacecraft,

coding the compressed data in said spacecraft in a concatenated Reed Solomon-Viterbi coding channel, comprising a Reed Solomon coder and interleaver followed by a Viterbi convolutional encoder;

transmitting to Earth the data coded by said concatenated Reed Solomon-Viterbi coding channel,

receiving on Earth the coded data transmitted from said spacecraft; and

decoding the received coded data, first by a Viterbi decoder followed by a Reed Solomon decoder and deinterleaver, the parameters E, J and I of the Reed Solomon portion of the coding channel and the parameters K and ν of the Viterbi portion of said channel being selected to provide a Reed Solomon codeword average error probability definable as P_{RS} being not greater than 10^{-4} with a system's signal-to-noise ratio, definable as E_b/N_o, being between 2 and 3db, J representing the number of bits per Reed Solomon symbol, E representing one-half the number of Reed Solomon parity symbols, I representing the number of interleaved Reed Solomon codewords, and where K represents the constraint length of the Viterbi encoder and $1/\nu$ is the code rate.

9. The method as described in claim 8 wherein said data is imaging data representing a two dimensional array of x by x picture elements, definable as pixels, each pixel in said first stream of bits being represented by y bits, said pixels being separable into source blocks, each source block comprising an array of z by z pixels whereby $m=y(z^2)$, where m is an integer, representing the number of bits per source blocks,

said entire array of x by x pixels being divisible into x^2/z^2 source blocks, the m bits representing each source block being compressed so that the average number of bits representing each source block in said second stream of bits is less than m

10. The method as described in claim 8 wherein the parameters of the Reed Solomon coding and interleaving means are $J=8$, $E=16$, $I=16$ and wherein the parameters of the Viterbi portions of said channels are $K=7$ and $\nu=2$

* * * * *

Reproduced from best available copy.

Appendix B

ABSTRACTS

N75-26207/1ST NTIS PRICES: PC A03/MF A01

15/5/8
CHANNEL CODING AND DATA COMPRESSION SYSTEM CONSIDERATIONS FOR EFFICIENT COMMUNICATION OF PLANETARY IMAGING DATA

JET PROPULSION LAB., CALIF. INST. OF TECH., PASADENA.
AUTHOR: PICE, R. F.
C4003A2 FLD: 09D, 62E, 45G STAR1224
1 SEP 74 130P
REPT NO: NASA-CR-140181; JPL-TM-33-695-REV-1
CONTRACT: NAS7-100
MONITOR: 18
MISC-REVISED.

ABSTRACT: END-TO-END SYSTEM CONSIDERATIONS INVOLVING CHANNEL CODING AND DATA COMPRESSION ARE REPORTED WHICH COULD DRASTICALLY IMPROVE THE EFFICIENCY IN COMMUNICATING PICTORIAL INFORMATION FROM FUTURE PLANETARY SPACECRAFT. IN ADDITION TO PRESENTING NEW AND POTENTIALLY SIGNIFICANT SYSTEM CONSIDERATIONS, THIS REPORT ATTEMPTS TO FILL A NEED FOR A COMPREHENSIVE TUTORIAL WHICH MAKES MUCH OF THIS VERY SUBJECT ACCESSIBLE TO READERS WHOSE DISCIPLINES LIE OUTSIDE OF COMMUNICATION THEORY. (AUTHOR)

DESCRIPTORS: *CODING, *DATA COMPRESSION, *INTERPLANETARY SPACECRAFT,

N78-28302/5ST NTIS PRICES: PC A02/MF A01

15/5/3
POTENTIAL END-TO-END IMAGING INFORMATION RATE ADVANTAGES OF VARIOUS ALTERNATIVE COMMUNICATION SYSTEMS

JET PROPULSION LAB., CALIF. INST. OF TECH., PASADENA.
AUTHOR: PICE, R. F.
E2484J3 FLD: 17B, 45C STAR1618
15 JUN 78 26P
REPT NO: NASA-CR-157263; JPL-PUB-78-52
CONTRACT: NAS7-100
MONITOR: 18

ABSTRACT: VARIOUS COMMUNICATION SYSTEMS WERE CONSIDERED WHICH ARE REQUIRED TO TRANSMIT BOTH IMAGING AND A TYPICALLY ERROR SENSITIVE, CLASS OF DATA CALLED GENERAL SCIENCE/ENGINEERING (GSE) OVER A GAUSSIAN CHANNEL. THE APPROACH JOINTLY TREATS THE IMAGING AND GSE TRANSMISSION PROBLEMS, ALLOWING COMPARISONS OF SYSTEMS WHICH INCLUDE VARIOUS CHANNEL CODING AND DATA COMPRESSION ALTERNATIVES. ACTUAL SYSTEM COMPARISONS INCLUDE AN ADVANCED IMAGING COMMUNICATION SYSTEM (AICS) WHICH EXHIBITS THE RATHER SIGNIFICANT POTENTIAL ADVANTAGES OF SOPHISTICATED DATA COMPRESSION COUPLED WITH POWERFUL YET PRACTICAL CHANNEL CODING.

DESCRIPTORS: *COMMAND AND CONTROL, *RANGE AND RANGE RATE TRACKING, *SPACECRAFT COMMUNICATION, *TELECOMMUNICATION, CHANNELS (DATA TRANSMISSION), CODING, DATA COMPRESSION, IMAGERY, LUNAR EXPLORATION, SPACE EXPLORATION

IDENTIFIERS: NTISNASA

Appendix C

"POSTPRINT"

BLOCK ADAPTIVE RATE CONTROLLED IMAGE DATA COMPRESSION

Robert F. Rice
Ed Hilbert, Jun-Ji Lee, Alan Schlutsmeyer

Original paper published in
the Proceedings of the 1979
National Telecommunications Conference
Washington, D.C.
November 1979

JET PROPULSION LABORATORY
California Institute of Technology
Pasadena, California

ORIGINAL PAGE IS
OF POOR QUALITY

BLOCK ADAPTIVE RATE CONTROLLED IMAGE DATA COMPRESSION

Robert F. Rice
Ed Hilbert, Jun-Ji Lee, Alan Schlutsmeyer

Jet Propulsion Laboratory
Pasadena, California 91103

Abstract

A block adaptive rate controlled (BARC) image data compression algorithm is presented. In its principal rate controlled mode, image lines can be coded at selected rates by combining practical universal noiseless coding techniques with block adaptive adjustments in linear quantization. Compression of any source data at selected rates of 3.0 bits/sample and above can be expected to yield visual image quality with imperceptible degradation. Exact reconstruction will result if the one-dimensional difference entropy is below the selected compression rate.

The compressor can also be operated as a floating rate noiseless coder by simply not altering the input data quantization. In this case, the universal noiseless coder assures that the code rate is always close to the entropy.

Application of BARC image data compression to the Galileo orbiter mission of Jupiter is discussed.

INTRODUCTION

This paper presents a one-dimensional Block Adaptive Rate Controlled (BARC) image data compression algorithm recently developed for applications having extremely high fidelity requirements such as archiving and certain scientific investigations. This development is an outgrowth of earlier work involving both channel coding and image data compression.

BARC will first be introduced in combination with a brief review of this related earlier work. Important functional and performance relationships will be described. Later sections will provide a more detailed definition of BARC.

AICS

Information processing research for deep space exploration evolved into the concept of an Advanced Imaging Communication System (AICS) shown in Fig. 1.[1]

AICS introduced a new approach to monochromic image data compression as well as a practical solution to the classic error sensitivity problem of compressed data. The latter solution is provided by concatenating an interleaved Reed-Solomon (RS) code with the familiar convolutionally coded/Viterbi decoded data link.[2],[3] The combined channel results in virtually error free communication at the same data rate required by the convolutional channel alone to provide an acceptable error rate for uncompressed imaging ($P_e = 10^{-3}$)†. Thus data rate does not need to be lowered to achieve an error rate acceptable to compressed data. Rate/fidelity tradeoffs involving purely source coding concepts can be considered as "end-to-end" communication system tradeoffs. The benefits derived may similarly be considered as end-to-end benefits. The implications of this approach are far broader than the deep space communication problem for which it was intended.

RM2. The AICS concept introduced in Ref. 1 includes an image compression algorithm called RM2. This technique provides a continuous flexibility to tradeoff rate vs. quality by allowing any compression rate (bits/sample) to be selected on each image frame. Image quality is monotonically related to the bits/sample used for coding. Thus a slightly higher bits/sample results in slightly better image reconstruction

†At this same signal-to-noise ratio, $E_b/N_0 = 2.5$ dB, uncoded PSK modulation would yield a bit error rate of about 1/50.

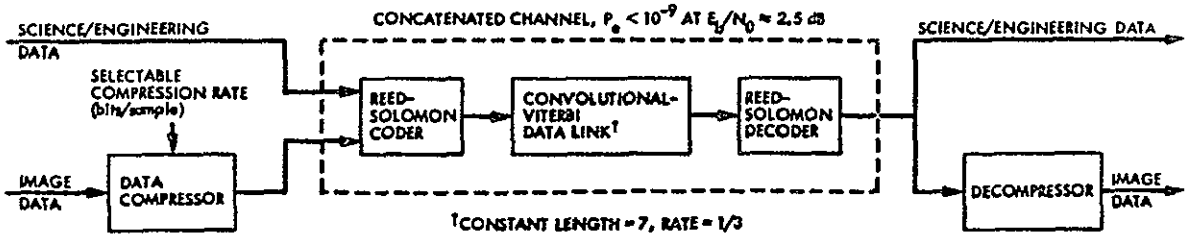


Fig. 1. Advanced Imaging Communication System (AICS)

Reproduced from best available copy.

ORIGINAL PAGE IS
OF POOR QUALITY

(up to exact reconstruction near the rate corresponding to the differential entropy of the data). Superior performance has been observed at all compression rates in comparison with standard adaptive techniques (adaptive cosine, Hadamard, hybrid, etc.)[4]

The RM2 rate control structure allows a fixed but arbitrary number of bits to be used per image frame by using a globally adaptive procedure to allocate bits according to activity measures taken from subpictures throughout an image. High activity areas generally receive higher allocations than low activity areas. In some cases a further refinement in rate allocation (and hence quality) can be simply obtained for selective "target" regions by-using pattern recognition techniques to weight the naturally occurring activity features.[5]

Future use of AICS in deep space exploration and other applications is expected to yield significant improvements in imaging information return capability over existing imaging communication systems. [6],[7]

A One-Dimensional Algorithm

The system constraints of several current applications made it difficult to capitalize on the broad range of selectable performance options provided by RM2. This led to the development of a simpler but related image compression algorithm aimed at satisfying these more restrictive performance and implementation requirements.

The resulting one-dimensional Block Adaptive Rate Controlled (BARC) algorithm has many similar functional and performance characteristics. Functionally both algorithms allow arbitrary selectable compression rates but the RM2 two-dimensional structure gives it a broader range of useful options. That is, at high rates of 3.0 bits/sample and above the performance of both algorithms is equivalent whereas at lower rates RM2 exhibits a decided advantage. On an absolute scale, degradation to visual image quality can be expected to be imperceptible at selected rates of 3.0 bits/sample and above for virtually any source data.

Both algorithms can be operated as floating rate noiseless coders with code rates close to the data differential entropy for all entropies above the neighborhood of 0.7 bits/sample.

Thus BARC basically provides the top end of the RM2 rate/quality performance range while needing only one-dimensional processing. The latter means that BARC is also applicable to other non-imaging forms of correlated data for which there are stringent fidelity requirements.

BARC

The operations illustrated in Fig. 2 are fundamental to the BARC algorithm. The primary rate controlled mode, to be discussed later, is simply obtained by utilizing these operations in a closed loop fashion.

Quantization

$\tilde{D}_i(0)$ represents a sequence of K data samples (e.g., 64) represented by m bits of linear quantization. $\tilde{D}_i(t_i)$, $t_i = 0, 1, 2, \ldots$ represents the same K samples of $\tilde{D}_i(0)$ after the linear quantization has been reduced by t_i bits. This is simply accomplished by a shift and round operation so that if x is a sample of $\tilde{D}_i(0)$ then $[(x + c_t)/2^{t_i}]$, $t_i \neq 0$ is the corresponding sample of $\tilde{D}_i(t_i)$ (and c_t is a roundoff constant). An approximation to the original sample x can be obtained as $\hat{x}$ where†

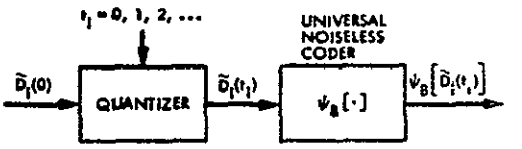


Fig. 2. Basic BARC Operations

$$\hat{x} = \begin{cases} x & , t_i = 0 \\ 2^{t_i}\left[\dfrac{x + c_t}{2^{t_i}}\right] & , t_i \neq 0 \end{cases} \qquad (1)$$

Noiseless Coding

Applying the Universal Noiseless Code operator $\psi_B[\cdot]$ in Fig. 2 to $\tilde{D}_i(t_i)$ yields the binary sequence

$$\psi_B\left[\tilde{D}_i(t_i)\right] \qquad (2)$$

from which $\tilde{D}_i(t_i)$ can be reconstructed exactly (hence the term noiseless coding). The original sequence $\tilde{D}_i(0)$ can be approximated using (1).

To be useful, operator $\psi_B[\cdot]$ must also provide a data representation which is efficient. Efficient noiseless coding means that the expected bits/sample required by $\psi_B[\tilde{D}_i(t_i)]$ is close to some practical measure of the minimum possible (while still allowing exact reconstruction of $\tilde{D}_i(t_i)$). For this problem this measure is of course the one-dimensional differential entropy.

A great many practical noiseless coding problems can be partitioned into two distinct subproblems. The first, preprocessing, basically corresponds to specifying appropriate decorrelation and relabeling operations while the second corresponds to the assignment of variable length codewords to the resulting preprocessed data.

Reversible preprocessing. For the specific imaging problem motivating the BARC development the preprocessing operations reduce to those shown in Fig. 3. Here RP[•] denotes the collective operations involved. These operations are reversible in that inverse operations applied to the output will exactly reconstruct the original input.

†$[\beta]$ is the integer part of β.

ORIGINAL PAGE IS
OF POOR QUALITY

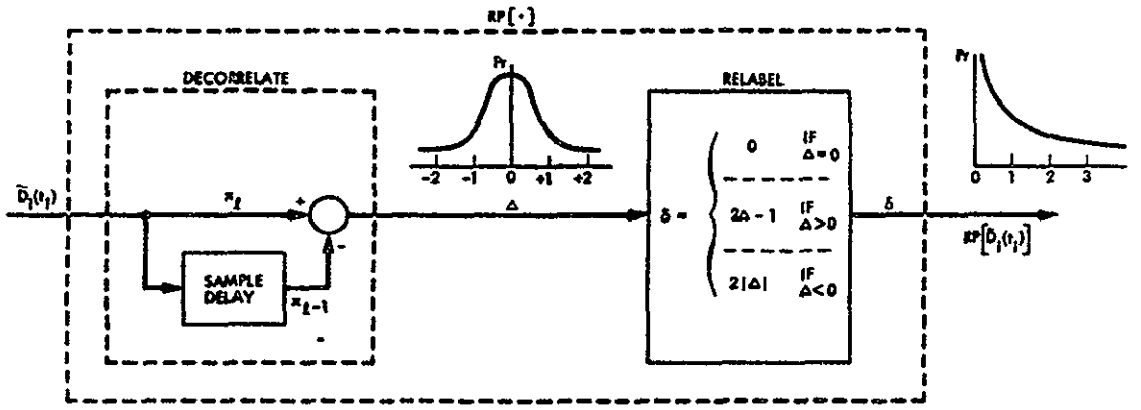


Fig. 3. Reversible Preprocessing Operations

As shown, differences between adjacent samples are first taken to yield an "approximately" memoryless sequence of samples indicated individually by the symbol Δ.† Because of considerable non-stationarity in the data source and the possibility of adjustments in t, significant variations in the entropy of Δ distributions can be expected. However, the Δ's will tend to remain distributed about zero in a uni-modal fashion. As a consequence, the following probability ordering of Δ values is consistently well approximated

$$Pr[\Delta = 0] \geq Pr[\Delta = +1] \geq Pr[\Delta = -1] \geq Pr[\Delta = +2] \geq \ldots \quad (3)$$

Thus it is a simple matter to map the Δ's into the non-negative integers $\delta = 0, 1, 2, \ldots$ such that with $p_j = Pr[\delta = j]$ the following condition remains well approximated‡

$$p_0 \geq p_1 \geq p_2 \geq p_3 \geq \ldots \quad (4)$$

The original noiseless coding problem has been reduced to the coding of an approximately memoryless source with known symbol probability ordering but with basically unknown values. That is, the entropy of δ distributions can be expected to vary considerably but without disturbing condition (4). Efficient coding means that the expected bits/sample required remains close to this entropy for all the entropy values that may occur. References 8 and 9 extensively treat this general problem, providing practical code operators which yield efficient performance in this sense for any entropy above zero. This is illustrated in Fig. 4. These results are extensions and revisions of earlier work described in Ref. 10.

We will not elaborate on these techniques here. It suffices to note that current breadboard versions of BARC employ code operator $\psi_8^J[\cdot]$, J = 16 defined in Refs. 8 and 9. Combining $\psi_8^J[\cdot]$ with the reversible preprocessing of Fig. 3, RP[·], completes the definition of the BARC Universal (works on all entropy values) Noiseless Code Operator $\psi_B[\cdot]$ shown in Fig. 5.

Rate Controlled Mode

A block diagram describing the BARC rate controlled mode is given in Fig. 6. This mode provides the ability to distribute a prescribed number of bits, N, over a one dimensional data sequence such as an image line. The basic idea is to partition the input data sequence into smaller data blocks (e.g., 64 samples) and then use "activity measures" for these blocks to determine which blocks should receive reductions in linear data quantization. The number of reductions and their location is determined such that a) when all the modified blocks are efficiently coded the number of bits used equals the number allowed for the input data sequence, and b) reductions in quantizations are first applied to blocks of higher activity (larger sample-to-sample variations). Subsequent paragraphs will specify this approach in more detail.

Let $\tilde{D}$ represent a data sequence partitioned into n blocks of K samples

$$\tilde{D} = \tilde{D}_1(0)\ \tilde{D}_2(0)\ \tilde{D}_3(0)\ \ldots \quad (5)$$

and where $\tilde{D}_i(t_i)$ has already been defined as data block $\tilde{D}_i(0)$ with each sample reduced in quantization by t_i bits (see Eq. 1).

†We are basically taking differences from a prediction that the next sample will be the same as the last. In most cases the improvements in performance from using a more sophisticated one dimensional predictor can be expected to be minor.

‡The entropy of the Δ or δ distributions is, of course, the same. It corresponds to the one-dimensional entropy mentioned earlier and appearing in Fig. 2, defined by the familiar equation $-\Sigma p_j \log_2 p_j$.

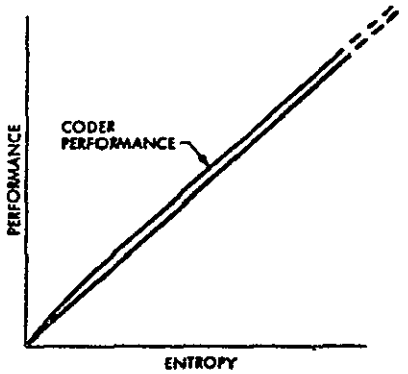


Fig. 4. Universal Noiseless Coder Performance

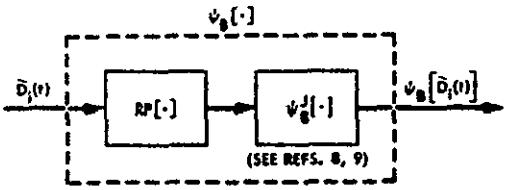


Fig. 5. BARC Noiseless Coder

The "activity" for $\tilde{D}_j(t_j)$ is defined as†

$$\alpha_j(t_j) = \left\{ \begin{array}{l} \text{Estimated bits to} \\ \text{code } \tilde{D}_j(t_j) \\ \text{noiselessly using } \psi_B[\cdot] \end{array} \right\} \approx \text{Entropy} \qquad (6)$$

Then we have

$$\alpha = \sum_{j=1}^{n} \alpha_j(0) = \begin{array}{l} \text{Estimated bits to code all of} \\ \tilde{D} \text{ such that exact reconstruction} \\ \text{is possible} \end{array} \qquad (7)$$

If N bits have been allowed for the coding of $\tilde{D}$ and $N > \alpha$, dummy bits actually have to be added. However, if $\alpha > N$ the bits needed to code $\tilde{D}$ must somehow be reduced by

$$\alpha - N \quad \text{bits} \qquad (8)$$

By observation, whenever the differential entropy for $\tilde{D}_j(t)$ is greater than about 3.5 bits/sample

$$E\left\{\alpha_j(t+1)\right\} \approx E\left\{\alpha_j(t)\right\} - K \qquad (9)$$

†The estimates in (6) can be easily obtained without the need to actually code $\tilde{D}(t_j)$ with $\psi_B[\cdot]$. [8], [9]

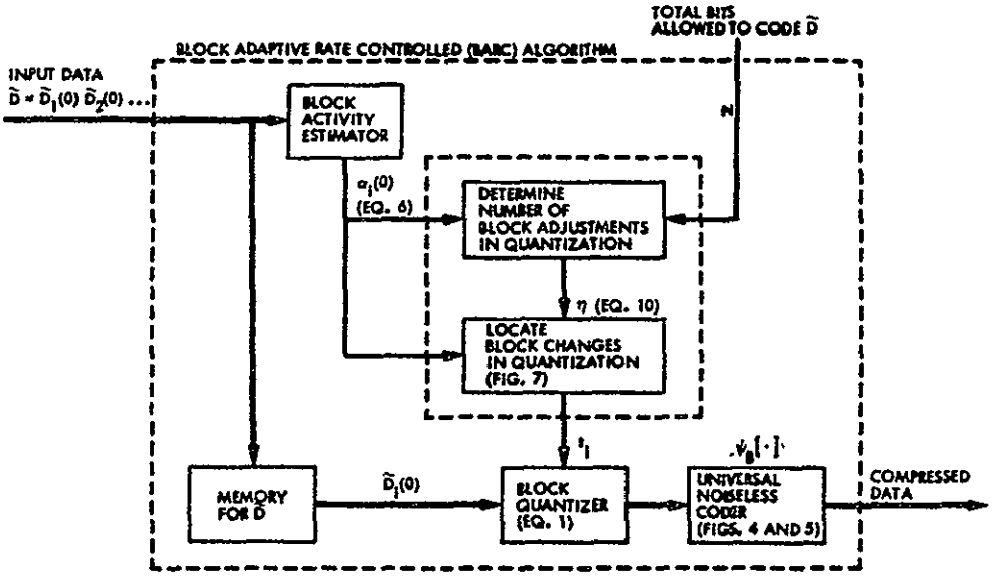


Fig. 6. BARC Block Diagram

ORIGINAL PAGE IS
OF POOR QUALITY

where $E\{\cdot\}$ denotes expectation. This means that a reduction in linear quantization by one bit can be expected to reduce the bits needed for coding by approximately one bit/sample. The total bits needed to code $\tilde{D}$ can be reduced by $\alpha - N$ bits by applying

$$\eta = \left\lceil \frac{\alpha - N}{K} \right\rceil \tag{10}$$

block reductions in quantization.

A larger $\alpha_i(t_i)$ indicates a higher data activity for the block, which also means the typical sample-to-sample transitions are larger. Clearly, a reduction in linear quantization is less damaging to blocks which have large transitions than to blocks which have small transitions. This suggests a simple algorithm for determining the location of the η block reductions in quantization. The algorithm appears in Fig. 7.

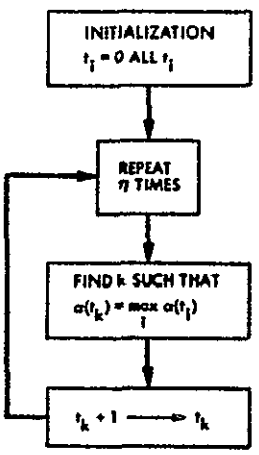


Fig. 7. Quantization Locator

Except for some subtleties the basic BARC definition is complete. Returning to Fig. 6, input sequence $\tilde{D}$ is stored while the t_i values are determined for each data block $\tilde{D}_i(0)$. Once this is accomplished, quantization adjustment followed by noiseless coding of the resulting $\tilde{D}_i(t)$ is initiated.

Adjustments for changes in t. The first Δ for $\tilde{D}_i(t_i)$ is the result of taking the difference between the first data sample in $\tilde{D}_i(t_i)$ and a "reference" sample generated from the last sample of the previous block $\tilde{D}_{i-1}(t_{i-1})$. If $t_i < t_{i-1}$ the expected fidelity of this reference sample needs to be upgraded to a level of quality corresponding to t_i. This can be accommodated by sending an additional $t_{i-1} - t_i$ bits at the beginning of a block. We will denote these bits by

$$LSB_i \tag{11}$$

Additionally, the need for an initial reference sample can be provided by transmitting the first sample of $\tilde{D}_1(0)$ separately (initializes $x_{\ell-1}$ in Fig. 3). We denote this by

$$REF = \begin{cases} \text{first sample} \\ \text{of } \tilde{D}_1(0) \end{cases} \tag{11}$$

Format. Noting also that the t_i values need to be transmitted (standard binary form) the data format can be defined as shown below in Fig. 8.

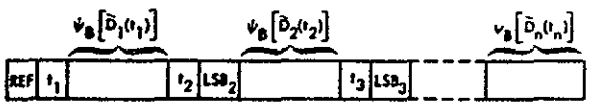


Fig. 8. Data Format

Minor adjustments. Because of some slight inaccuracies in the $\alpha_i(t_i)$ estimates the actual bits required to code $\tilde{D}$ may not match up precisely with the allowed N bits. In some applications this is of no consequence, whereas in others it may be a strict requirement. For the latter case there are several alternatives which may be applied separately or in combination.

a) If the number of bits required to code $\tilde{D}$ exceeds N, then coding terminates when the bits used equals N (e.g., a few picture elements are lost at the end of a TV line).

b) buffering: If the bits required exceed N by λ bits, adjust the number of bits allowed in the next $\tilde{D}$ sequence to $N' = N - \lambda$.

c) epsilon. The potential for exceeding N bits can be reduced by modifying the numerator in (10) to $\alpha - N + \epsilon$. The choice of ϵ can be picked to also include the effect of overhead bits needed for REF, LSB_i and t_i.

d) Continually update the t_i as $\tilde{D}$ is coded.

If the number of bits required to code $\tilde{D}$ is less than N, dummy bits are added.

Other observations. In most image applications t values of two or less are completely adequate to ensure selected code rates down to 3 bits/sample (data entropies up to about 5 bits/sample). Requirements for larger values of t may be accomplished by a front end "line-split" which truncates off the least significant bits of all samples of $\tilde{D}$. The decision to perform the split(s) is made only if the calculated number of quantization reductions, η in Eq. 10, is large. Each line-split is basically equivalent to increasing each t_i by one. The line-split approach can also be used to more easily extend the efficient performance range of $\psi_B[\cdot]$ to higher entropies when operating in a floating rate noiseless coding mode (all t_i = 0). [8]-[10]

ORIGINAL PAGE IS
OF POOR QUALITY

DISCUSSION

With only slight variations the BARC algorithm described here is generally applicable to most real one-dimensional correlated data sources for which the fidelity requirements are very high. The universal noiseless coding techniques used by BARC but elaborated on elsewhere[8],[9], have a much broader applicability.

The effect of bit errors will propagate so that BARC suffers from the familiar error sensitivity problem of compressed data. Other than remedial operations such as the occasional insertion of sync words, BARC should be used in an environment where error events are rare. For deep space communication this classic problem was solved by the concatenated Reed-Solomon/convolutional-Viterbi channel described earlier (Fig. 1).

The concatenated channel and an 800 Kbit/sec CMOS version of BARC have been implemented for the Galileo orbiter mission of Jupiter.
BARC will be applied to 8 bit/sample imaging data and operated at a fixed 3.24 bits/sample. This version employs a single line-split to extend the efficient noiseless coding range to entropy values from 0.7 to 6 bits/sample.

The concatenated Reed-Solomon/convolutional-Viterbi channel will also be incorporated on the International Solar Polar Project. Both BARC and RM2 are currently being studied for application to Solar Polar imaging devices (Coronograph and X-ray).

In earth based applications both algorithms are being investigated for compression of NOAA weather satellite data.

ACKNOWLEDGMENT

The research described in this paper was carried out by the Information Processing Research Group of the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the National Aeronautics and Space Administration under contract NAS7-100.

REFERENCES

1. R. F. Rice, "An Advanced Imaging Communication System for Planetary Exploration," Vol. 66, SPIE Seminar Proceedings, Aug. 21-22, 1975, pp. 70-89.

2. R. F. Rice, "Channel Coding and Data Compression System Considerations for Efficient Communication of Planetary Imaging Data," Chapter 4, Technical Memorandum 33-695, Jet Propulsion Laboratory, Pasadena, CA, June 15, 1974.

3. J. P. Odenwalder, "Concatenated Reed-Solomon/Viterbi Channel Coding for Advanced Planetary Missions: Analysis, Simulations and Tests," submitted to Jet Propulsion Laboratory by Linkabit Corp., San Diego, CA, Final Rep., Contract 953866, Dec. 1, 1974.

4. R. F. Rice, "RM2: rms Error Comparisons," Technical Memorandum 33-804. Jet Propulsion Laboratory, Pasadena, CA, Sept. 15, 1976.

5. R. F. Rice, "A Concept for Dynamic Control of RPV Information System Parameters," Proceedings of the 1978 Military Electronics Exposition, Anaheim, CA, Nov. 1978.

6. J. Cutts and L. Lebofsky, "Evaluation of the RM2 Image Data Compression Technique for Outer Planet Missions with the Pioneer Spacecraft," submitted to Jet Propulsion Laboratory by Planetary Science Institute, Pasadena, CA, Final Rep., Contract 954152, Nov. 1975.

7. R. F. Rice, "Potential End-to-End Imaging Information Rate Advantages of Various Alternative Communication Systems," JPL Publication 78-52. Jet Propulsion Laboratory, Pasadena, CA, June 15, 1978.

8. R. F. Rice, "Some Practical Universal Noiseless Coding Techniques," JPL Publication 79-22. Jet Propulsion Laboratory, Pasadena, CA, March 15, 1979.

9. R. F. Rice, "Practical Universal Noiseless Coding," SPIE Symposium Proceedings, Vol. 207, San Diego, CA, August 1979.

10. R. F. Rice and J. R. Plaunt, "Adaptive Variable Length Coding for Efficient Compression of Spacecraft Television Data," IEEE Trans. Commun. Technol., Vol. COM-19, part I, Dec. 1971, pp. 889-897.