ACCELERATING DATA FOR THE WARFIGHTER

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ABSTRACT

A methodology for efficiently integrating geosynchronous satellite links into communications networks by employing modern digital technology, in particular the asynchronous transfer mode (ATM), is explained. The concept of seamless interoperability is examined, and a vital C4I U.S. Army network (the Warfighter Information Network) which will employ ATM is described. ATM cell structure is explained, and it is shown that the header error correction byte can be stripped from the cell, and idle ATM cells removed, to accelerate the delivery of data.

A purpose-designed interface, COMSAT's ATM Link Accelerator, is then described which uses the header error correction byte and idle cells, as well as both header and data compression, to efficiently provide adaptive error correction for error-free transmission of ATM over the satellite link, while maximizing data throughput. The results of tests conducted using this network interface equipment in two separate CECOM facilities (the DSCS ITF at Ft. Monmouth, New Jersey, and the Trojan ATM Test Laboratory at Ft. Huachuca, Arizona) are presented and discussed.

INTRODUCTION

Every member of the Armed Forces has heard that, to be effective, every unit must be able to move, shoot, and communicate. All of these abilities are vital, and all three must be woven into doctrine, whether it is Joint Vision 2010, the U.S. Army's Force XXI, and any other supporting concepts. These abilities must also be put into practice. This paper addresses a subset of communicating, namely the efficient melding of the advantages of geosynchronous satellite coverage and flexibility with the attributes of asynchronous transfer mode (ATM) digital networking technology.

The concept of seamless interoperability is discussed first, primarily in the context of the Army's Warfighter Information Network (WIN). Since the WIN will employ various transmission media to deliver the required service to users, the interrelationship of transmission engineering as applied to satellite communications links and digital network engineering is discussed. It is shown that satellite communications links can be effectively and seamlessly integrated into evolving digital networks. Hardware that can accomplish this—specifically, the ATM Link Accelerator 2000 (ALA-2000) developed at COMSAT Laboratories*—is described, and results of measured performance over a geosynchronous satellite are presented.

SEAMLESS INTEROPERABILITY

The first major step toward a seamless network, be it the WIN or any other, was probably the digital encoding of voice signals. Algorithms that could effectively transmit voice as a bit stream began with 64-kb/s pulse-code modulation. In pace with improvements in digital microprocessor technology and the development of less expensive memory, the voice encoding rate for toll-quality voice transmission dropped first to 32 kb/s, then to 16 kb/s, and now has reached 8 kb/s.

The first digital circuit multiplication equipment (DCME), designed primarily to increase capacity over digital voice links, dealt with voiceband data (which were prevalent at the time) by invoking a separate encoding algorithm to transmit such data, with adequate fidelity, over the long-haul satellite communications link. Today, incoming data are demodulated from the form in which they are received from a terrestrial switch, and are sent over the long-haul link as a digital bit stream. At the far end of the satellite link, the data are again put into the voiceband modem format and sent on to the end user. The end user is probably unaware of how the data are processed during their journey through the overall communications network (and probably doesn't care). To this user, the network appears seamless.

*The COMSAT ATM Link Accelerator was recently renamed the CLA-2000™ ATM to reflect the development of new variants specifically tailored to frame relay and TCP/IP. Some of the technology in the CLA-2000/ALA-2000 is proprietary, and patents have been applied for.

The demand for more and more bits of information seems insatiable, and currently is driven by requirements for data, imagery, e-mail, voice, video, etc., at every command level in today's Armed Forces. This demand is expected to continue to increase. A fully digitized heavy Army division is expected to include some 5,000 computers; even a non-digitized division will include well over 1,000. A recent article predicts a need for 20 to 80 Mb/s of data throughput to a single aircraft carrier [1].

While it would be convenient for the engineers who must interconnect the end users of information (i.e., the customers) were there a single, homogeneous transmission medium, this cannot be the case. Signal planners, engineers, and operators have long recognized this. Rienzi [2], in his very readable book on communications/electronics in the Vietnam conflict, has pointed out that planners of future military communications architectures must consider all transmission media in deciding what best meets the need in any given situation.

It has been suggested that geosynchronous satellites may not have a role in evolving digital networks. The reasons generally given—often by those who propose expensive, unproved alternatives or terrestrial cables—are the transmission delay (which is nominally 250 ms one way, due to the distance from earth to the geostationary arc and back) and the variable quality of the satellite-radio link [generally expressed as bit error ratio (BER)]. While the time delay is inescapable, the transmission quality of the satellite link can be made indistinguishable from that of cable systems, and relevant inconveniences in digital networking technology can also be dealt with effectively. With this accomplished, the network user need not be concerned with the path that information takes, and a seamless network results.

THE WARFIGHTER INFORMATION NETWORK

The Warfighter Information Network (WIN) is the Army's common-user C4I tactical network, which will provide for information transmission and exchange among commanders, staff elements, and sustaining bases for the Army of the 21st century. It is intended to achieve and sustain information dominance for the Commander. Its evolution and development are tied to the advent of the digitized force structure, as set forth in the Army Digitization Master Plan (ADMP) [3]. Figure 1 is a functional depiction of the WIN.

The WIN is based on ATM digital network technology, which is discussed in greater detail below. ATM is a

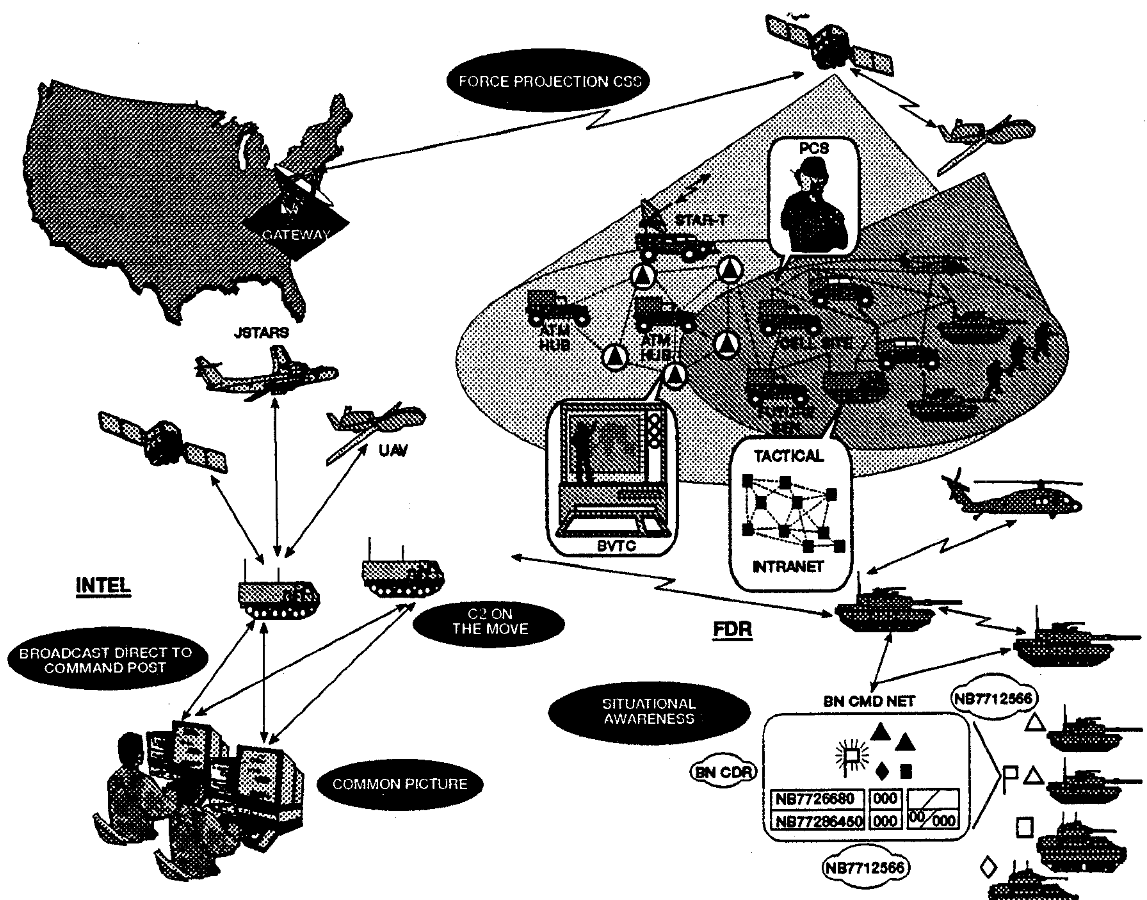

Figure 1. WIN XXI Functional Depiction

development of the commercial telecommunications community, and was selected for the WIN for good reason. ATM is well suited to the concurrent delivery of applications such as voice, video, and data, in any combination. Using ATM, a single customer can take advantage of videoconferencing, imagery, and voice concurrently, which is a true multimedia capability. While each of these applications has different characteristics and sensitivities, all are readily accommodated on ATM-based networks. The individual bit rates of multiplexed information flowing over a network path can be varied, which provides flexibility and can increase transmission efficiency.

The WIN consists of the following intertwined component threads:

- Power Projection/Sustaining Base
- Satellite Transport
- Terrestrial Transport
- Tactical Internet/Combat Net Radio
- Information Services
- Information Systems
- Network and Systems Management.

From the perspective of Joint Doctrine [4],[5], it would be a mistake to rule out *a priori* any transmission medium for the various service/system components of the WIN. In fact, satellites are the primary resource for communicating between sustaining bases in CONUS and commanders in a remote Area of Responsibility (AOR). Consider the AOR for the U.S. Pacific Command. It will be vital for U.S. forces to communicate over distances that could stretch from the East Coast of Africa to the West Coast of the United States. Terrestrial transmission media are not well suited to spanning such distances, or even relatively small areas of this AOR. In addition, they may be vulnerable to disruption, or unavailable due to required maintenance. A satellite-based infrastructure can be implemented quickly, can serve virtually any part of an AOR, and is ideal for supporting the demands of the extended battlespace concept, split-base operations, and joint/coalition warfare.

As far back as the fall of 1993, COMSAT demonstrated to the Defense Information Systems Agency (DISA) ATM-based, concurrent, multimedia applications (specifically telemedicine and remote (air) mission planning) over a commercial satellite link [6]. This was in the context of service between a Sustaining Base Facility in CONUS and a Deployed Joint Task Force Headquarters. The information rate transmitted was 45 Mb/s (T3). Earlier this year COMSAT, working with two long-distance carriers, implemented an ATM-based Internet service via geosynchronous satellite between the United States (Puerto Rico) and South America. Information rates are 45 Mb/s outbound from the United States and 8.448 Mb/s inbound from South America. Important components in these links are ATM interfaces developed by COMSAT with the specific intent of facilitating ATM service via geosynchronous satellite links. One of these interfaces is discussed in greater detail below, along with the results of performance tests.

DIGITAL NETWORK TECHNOLOGY

Over the last two decades, engineers have taken a fresh look at communications networks from the perspective of building a digital communications network in an orderly manner, while allowing for expansion and modification. By 1984, the International Standards Organization (ISO) had defined a "Reference Model for Open Systems Interconnection" (OSI Model) [7]. The seven layers that make up this model range from the Physical Layer, which is the actual transmission path, and culminate in the Application Layer. These higher level requirements come into play as the connection approaches, and reaches, the end user. At each layer, rules for interconnection, or protocols, are defined.

The OSI Model provides an open-network framework for a variety of digital networking technologies, such as the Integrated Services Digital Network (ISDN), frame relay, TCP/IP (which underpins the Internet), and ATM. These technologies are sufficiently pervasive that they do not always fit into a single layer, as defined by the model. For example, at least two of the OSI Model layers that sit atop the Physical Layer—the Data Link Layer and the Network Layer—apply to ATM.

The ATM itself is not affected by transmission delay, as evaluations discussed later in this paper confirm. The protocols embedded in other digital networking techniques, such as the Transmission Control Protocol (TCP), which is at the higher, Transport Layer in the OSI Model, are sensitive to transmission delay; however, a discussion of this aspect of digital networking is beyond the scope of this paper. COMSAT has established a broadband digital test facility that can simulate the delay and BER of a satellite link. Its purpose is to allow potential U.S. customers for INTELSAT space segment to test and refine applications for use over geosynchronous satellite links

The military communications community has for some time been exploiting advances in commercial communications technology, and has adopted standards developed in such commercial forums as the International Standards Organization (ISO) and the International Telecommunication Union - Telecommunications Standardization Sector (ITU-T). This should benefit all concerned, so long as these standards do not preclude any useful transmission medium. Communications system engineering texts of a generation ago refer to "a fading channel," which is characteristic of all radio links, including those via satellite. While the modulation techniques and content of signals being transmitted over these channels have changed due to the digitalization referred to above, the channel characteristics have not.

ATM is a means of partitioning a stream of digitized data, voice, imagery, or other such information, into a series of conveniently sized packages, or cells, for transmission. Each cell contains 53 bytes, with each byte being an "octet" of eight individual bits. Five of the bytes are reserved for the header or address tag, leaving 48 bytes (384 bits) for the payload. An analogy that may help in visualizing the ATM cell is the CONEX container, which should be well known to members of the Armed Forces. Recall that these steel containers are all the same size, thus expediting their shipment. When full, the container is closed and the address or identity of the recipient (in the form of a stenciled legend or tag) is attached. The standard-sized interior of the CONEX container is analogous to the ATM payload, and the stencil and tag are analogous to the ATM cell header.

In lieu of BER (a metric well understood by the satellite system engineer), cell error ratio (CER), cell loss ratio (CLR), cell misinsertion rate (CMR), cell transfer delay (CTD), and cell delay variation (CDV) are parameters of interest to the digital network engineer, with CER and CLR being the most commonly quoted. Commercial standards for ATM performance and objectives, as well as processing algorithms for ATM, over satellite links are being developed in the ITU - Radio Sector and in the Telecommunications Industries Association.

ATM performance recommendations are tailored to terrestrial, fiber optic transmission characteristics. This means that links transmitting ATM must have a good BER, or the ATM cell must be made more resistant to the effects of errors. In short, an interface device is necessary. While the 5-byte header, or address information, in the ATM cell does commit 1 byte to error correction, this only hardens the address against the randomly distributed errors characteristic of terrestrial cables. If the address is incorrect, the effect is much the same as it would be for a CONEX container: it would not reach the user who needs it.

The header error correction byte does not prevent damage to the payload bytes. It may not be necessary to protect these against corruption if the transmission medium exhibits randomly distributed errors occurring at a sufficiently low rate. Returning to the CONEX container analogy, if the recipient should open a properly tagged and stenciled container, but the contents are damaged or the container is empty, the effect is no better than if the wrong customer or user receives a container of undamaged but useless items.

Another characteristic of ATM is that not all cells contain useful information. These idle cells can be identified and eliminated from the transmitted digital bit stream. Further, corresponding bytes may be pooled with the header error correction bytes and used to carry error correction coding for the useful data, thus accelerating its delivery. How this may be applied is discussed below in the context of the ALA-2000.

SATELLITE SYSTEM ENGINEERING CONSIDERATIONS

If the advantages of geosynchronous satellites are to be fully exploited by the WIN, it is necessary to ensure that ATM is successfully interfaced to the satellite link. Almost any BER desired can be obtained over a satellite link; the trick is to achieve this economically. Availability (the percentage of a year during which the link provides performance better than a threshold value) is also a requirement. For instance, COMSAT's major customers demand a BER of 1×10^{-6}, or better, over their satellite links, for all but about 4 hours per year. This is achieved by intelligent selection of satellite resource, earth station size, modulation technique, and forward error correction (FEC).

The FEC approach used in most satellite modems is convolutional coding and Viterbi decoding. The FEC is implemented in discrete levels called "*x/y* rate coding," where *x/y* is the ratio of user traffic to transmitted bits. Typical coding rates, in order of increasing error correction capability, are 7/8, 3/4, 2/3, and 1/2. The coding rate is generally selected to optimize the use of the satellite bandwidth and power resource by taking into account the characteristics of the satellite transponder and the earth stations. While there will be far fewer errors on a link, those that do occur will no longer be randomly distributed, but will occur in clusters [8].

The satellite system engineer may also use Reed-Solomon (R-S) outer coding to supplement the FEC, in order to achieve the link performance discussed above. In the late 1980s, COMSAT developed a technically effective and cost-effective implementation of R-S coding [9] and made it available to the INTELSAT community. During an early transpacific test, a link equipped with this R-S outer codec achieved an average BER of 5×10^{-10}, as compared with a BER of 1×10^{-6} for the companion "control" carrier which was not so equipped [10]. In addition, COMSAT's R-S implementation included interleaving to randomize the bursts of errors caused by the FEC. With the commercialization of R-S outer coding available, the satellite system engineer now had all the tools necessary to support networks providing new services such as Internet and digital teleconferencing.

A satellite link must be designed to provide satisfactory service when degraded by (for example) rain attenuation, to the degree seen only for a few hours in a year. However, for most of that year link performance will be very much better. Even without R-S outer coding, a typical link over the INTELSAT System would be expected to demonstrate a BER of 1×10^{-9} or better for 99.4 percent of the time (i.e., for all but about 55 hours in a year). R-S coding extends this performance to all but a few hours per year.

THE ATM LINK ACCELERATOR

The use of R-S coding in combination with FEC during any but the most severely degraded conditions can result in needlessly inefficient use of the satellite bandwidth resource. Implementations of R-S coding available in satellite modems cannot adapt to the instantaneous characteristics of the transmission path. COMSAT's ALA-2000 makes the R-S coding adaptive, in discrete steps, to the varying characteristics of the satellite link. These discrete levels of R-S coding make use of the header error correction byte and the bytes corresponding to empty ATM cells. At each level, an additional pair of R-S "checkbytes," ranging from 0 (no R-S coding) to 20 (maximum R-S coding), is employed by the ALA-2000. The checkbytes are dynamically increased or decreased, based on the instantaneous quality of the transmission path. The sending ALA determines the number of checkbytes to be used by continuously communicating with the receiving ALA to obtain feedback on the quality of the satellite link.

Because the ALA-2000 operates on the ATM cells and is "aware" of user traffic, it has the ability to buffer the user cells and integrate overhead in what would normally be idle ATM cells. This, in conjunction with removal of the header error correction byte, minimizes throughput degradation over the link when a high degree of R-S coding is required. This adaptive R-S coding implementation, combined with the ATM cell "intelligence" of the ALA, results in very efficient use of the satellite bandwidth.

The satellite bandwidth resource allocated to a link equipped with the ALA must accommodate the information rate with maximum R-S coding. This total transmission rate is usually set to one of the standard digital hierarchical rates. The real gain is seen by the user, who achieves greater throughput from a given satellite resource whenever the adaptive R-S coding is less than the maximum. This is the case during all but the most degraded conditions.

The ALA-2000 can also further compress the remaining 4 bytes in the ATM header (recall that the 5th, error correction, byte is already otherwise employed) into 2 bytes. For the 53-byte ATM cell, this provides an additional 3.8 percent improvement in throughput, with no loss in functionality to the user. Also, raw user data such as TELNET, FTP, SMTP, and synchronous serial traffic tend to be very compressible. The ALA-2000 dynamically compresses user traffic on a per-virtual-channel (VC) level. This compression is performed at line speeds and is 100 percent lossless, to ensure that user data are not corrupted. This per-VC implementation gives the user the flexibility to either apply compression (such as to TCP/IP router traffic) or not [in cases where the data are pre-compressed (e.g., digital video) or encrypted].

From an external perspective, the ALA-2000 is an interface device. Its ATM port drops and inserts a bit stream of up to 8.448 Mb/s from a DS-3 trunk. (Other ATM port options are available.) This bit stream contains ATM cells, ready for exchange with ATM network devices such as switches and routers. The wide area network (WAN) port of the ALA-2000 provides a digital bit stream at up to 8.448 Mb/s to the input port of a satellite modem. On the receiving side, the WAN port accepts the bit stream from the modem and transfers an ATM bit stream, with cell structure intact, ~~to~~ the ATM port.

TESTS BY U.S. ARMY AGENCIES

The ALA-2000 was tested independently at two Government evaluation facilities: the Defense Satellite Communication System (DSCS) Integrated Test Facility (ITF), U.S. Army CECOM, Ft. Monmouth, New Jersey, and the Information Systems Engineering Command (ISEC) TROJAN ATM Evaluation Lab, U.S. Army CECOM, Ft. Huachuca, Arizona. Each site evaluated separate aspects of the functionality of the ALA-2000.

Testing at the DSCS ITF

At the ITF, Ft. Monmouth, extensive tests of the CLR and CER, as a function of E_b/N_o, were conducted to verify the ability of the ALA-2000 to reliably transfer user data across degraded satellite transmission links. Preliminary results were reported at MILCOM '97 [11].

The ITF verified the performance of the adaptive R-S coding error correction implemented in the ALA-2000, as compared to the "static" R-S error correction implemented in satellite modems. The ATM performance metric was the sum of the CER (# errored cells / # total cells) and the CLR (# discarded cells / # total cells). Figure 2 shows CER + CLR as a function of E_b/N_o. The parameter is the R-S coding. In one case there is no R-S coding; in the second case R-S coding is provided in the modem; and the third case reflects the ALA-2000 adaptive R-S implementation.

Both adaptive and static R-S coding significantly improved ATM performance compared to a satellite link using only FEC. With no R-S coding, the minimum DISN ATM requirement of a CLR of 1 x 10^{-7} [12] clearly requires significantly greater E_b/N_o than with either variant of R-S coding. While at an E_b/N_o greater than 5.0 dB, this minimum ATM performance was achieved with either R-S implementation, the adaptive ALA-2000 approach met the requirement at an E_b/N_o of 4.0 dB.

Testing at the TROJAN ATM Evaluation Lab

To complement the ITF testing, ISEC investigated ATM throughput by conducting several evaluations to document the throughput obtained through a satellite link employing the ALA. The ATM data were first looped locally before the satellite modem, then looped back through a commercial geosynchronous satellite. Finally, the ATM data were looped through a satellite transmission path to a distant earth station equipped with the ALA-2000. As expected, there was no measurable difference in throughput attributable to the transmission delay, thus demonstrating that ATM throughput is independent of delay.

In the first evaluation, the checkbytes of the ALA-2000 were manually varied from 0 to 20, and the corresponding throughput measured. In the second evaluation, the ATM header compression feature of the ALA-2000 was activated, the checkbytes were again varied from 0 to 20, and the corresponding throughput was measured and recorded. The results of these two evaluations are shown in Figure 3. As described above, header compression provided a consistent improvement in throughput of about 3.8 percent whenever the adaptive R-S coding was invoked.

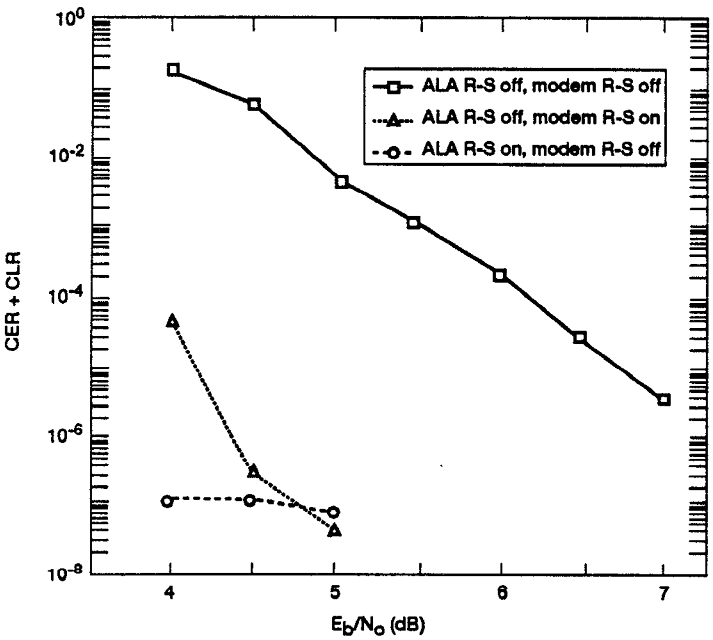

Figure 2. CLR + CER *vs* E_b/N_o, With R-S Coding as the Parameter

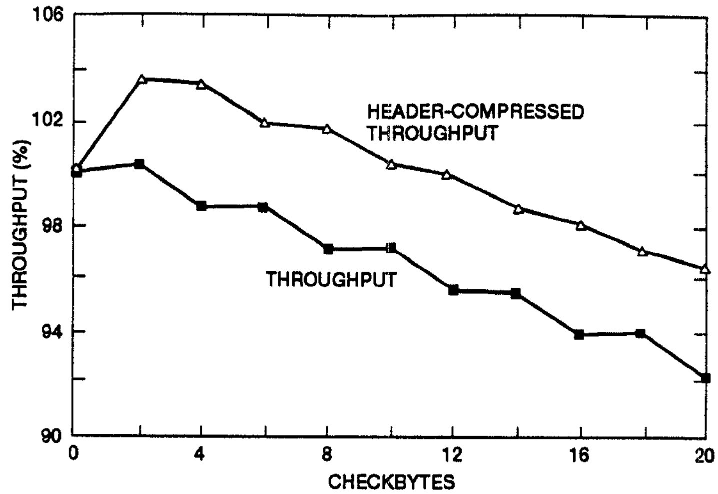

Figure 3. Throughput With and Without Header Compression, as a Function of Checkbytes Employed

The final evaluation by ISEC measured the ability of the ALA to compress user data. Two types of data were used in this evaluation. The first was an uncompressed Microsoft Exchange mail file. The second used a commercially available compression utility to compress the same Microsoft Exchange mail file. Each of these test files was then fed continuously into the ALA on a compressed VC, and the throughput measured and recorded. Table 1 summarizes the throughput performance obtained.

For the uncompressed test file, the percentage decrease in available throughput due to the R-S coding checkbytes was calculated to be 8.68 percent. The average measured throughput decrease was determined to be 0.96 percent per 2 checkbytes, or 0.48 percent per checkbyte. For the compressed test file, the percentage decrease in available throughput due to the introduction of the R-S coding checkbytes was calculated at 7.38 percent. The average measured throughput decrease was determined to be 0.82 percent per 2 checkbytes, or 0.41 percent per checkbyte.

Table 1. Percentage Throughput vs Number of Checkbytes

	Throughput (%)	
Checkbytes	**Uncompressed Test File**	**Compressed Test File**
Minimum (2)	227.7	92.3
Maximum (20)	208.0	85.5

CONCLUSIONS

There is no doubt that geosynchronous satellites can be readily integrated into digital networks through the use of ATM. Thus, the military communicator can confidently meld this modern digital network technology into military communications of the 21st century. The authors believe that the test results obtained by CECOM at the DSCS ITF, Ft. Monmouth, and the Trojan ATM Test Lab at Ft. Huachuca amply demonstrate that satellite transmission and ATM technology are fully compatible, especially when a purpose-designed interface such as COMSAT's ALA-2000 is employed.

ACKNOWLEDGMENTS

The authors are particularly appreciative of the support and encouragement provided by S. Miller, VP, Engineering and Operations, COMSAT World Systems (as well as her critical review of this paper); J. Mattingly, President, COMSAT Satellite Services; and R. C. Gustavson, Transmission Systems Directorate, U.S. Army Information Systems Engineering Command. They also wish to acknowledge the roles of A. Agarwal, COMSAT Laboratories, who conceived of the ALA-2000 and led its implementation; and S. Miller, who led development of a cost-effective implementation of Reed-Solomon coding for digital satellite communications. The ongoing work of D. Khalil and M. Patel at the DSCS ITF is also acknowledged. Discussions with R. Kibler and L. Kingsley of COMSAT were also very helpful.

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