ADVANCED TECHNOLOGY TESTBEDS FOR DISTRIBUTED, SURVIVABLE COMMAND, CONTROL AND COMMUNICATIONS (C^3)

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ABSTRACT

Two testbeds have been established to transfer emerging technology from the research community to the military thereby providing a basis for developing new military concepts for force effectiveness and survivability. Although still emerging, these technologies are now being presented to the user to make it possible to investigate (today) command, control and communications (C^3) concepts that might otherwise not be considered for another decade. The technologies being transferred include: automated tactical reporting systems, advanced packet-switched communication, automated man-machine interfaces, communication network and internetwork environments, automated display and analysis of data, and techniques for automatically disseminating information into redundant/distributed data bases. Expectations are that the testbeds will ultimately lead to the definition of military distributed C^3 architectures that will permit a commander to execute his mission in the "battlefield of the future" more effectively.

INTRODUCTION

In military confrontations, the United States forces will face a highly dynamic environment. This environment results from two factors: (1) the increased kill-power and accuracy of modern weapon systems and (2) the response to this threat--the high mobility of forces during battle. This environment greatly complicates effective command, control, and communications (C^3) of our forces. Furthermore, the integration of computer systems and the attendant need for real-time information (data) transfer in a crisis, compounds the problems of developing a military structure capable of surviving and functioning in a nuclear engagement.

However, significant progress has been made in the areas of information management and processing; distributed, survivable communication systems; and new military concepts in distributed C^3 that will enhance our ability to survive in this environment. In this paper, we discuss two testbeds that have been established to transfer emerging technology from the research community into the military and to provide a basis for developing new military concepts for force effectiveness and survivability.

The technologies being integrated into the testbeds are being developed through the Department of Defense (DoD). Although still emerging, these state-of-the-art technologies are presented to the user so that advanced concepts in distributed C^3 can be formulated. This technology transfer makes it possible to investigate (today) concepts that otherwise might not be considered for another decade. Similarly, by obtaining feedback from the user during the development of this technology, the research community can better ensure that their efforts will satisfy user requirements.

Of these two advanced-technology testbeds, one is directed primarily toward tactical users; the second, toward strategic users. In both testbeds, a close relationship has been established between the military and the organizations involved in transferring and developing advanced technologies. This close association has been an important factor in the success of the testbeds to date.

These testbeds are not paper studies, but are in-the-field programs in which the user participates directly in the application and transfer of the technologies.

TACTICAL DATA DISTRIBUTION TESTBED

Distribution of computer-provided data must eventually be as convenient and comfortable for the military commander and his staff as voice communications are today. Digital data networks will probably provide secure, reliable, easy, instantaneous access to information (data) sources far exceeding those currently available. This increase in available information comes from: (1) systems that can better monitor the up-to-date status of friendly forces, (2) intelligence systems that collect and display critical information about enemy forces, and (3) the many embedded processors that exist in modern, automated systems that the military is placing in its inventory.

Because of the increase in available data, the drive for survivability of our ground forces in a nuclear war, and the high degree of mobility that the enemy forces will have, the miliary is interested in developing concepts in distributed command and control (C^2), data distribution systems, and advanced information processing techniques (e.g., redundant data bases).

Using advanced technologies developed through the Information Processing Techniques Office (IPTO) of the Defense Advanced Research Projects Agency (DARPA), SRI International is providing the system engineering and technical direction required to establish an Army Data Distribution System (ADDS) testbed. This testbed provides a facility for the evaluation of and experimentation with the Army's advanced C^3 concepts.

The overall trend in the use of digital data for C^2 and new Army concepts in survivable command structures has progressed to the point where many difficult problems have been identified. For

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example, the Army's Combined Arms Combat Development Activity (CACDA) has developed a concept, called the cellular command post (CCP), that attempts to ensure the survivability of a command center in a tactical nuclear environment through distribution and replication of the functional areas presently consolidated into one tactical operation center (TOC). In this concept, division TOCs are divided into cells. These cells are replicated at least twice, and for survivability, they are situated several kilometers apart. This TOC architecture highlights the problem of distributing C^2 information and retaining concurrent replicated data bases at the cells. If a "backup" cell is to effectively assume the responsibility of a disabled primary cell, then its C^2 information must be as current as that residing in the other cell. The division cellular CP, however, is only a microscopic view of the battlefield. This concept could be implemented from brigade through corps echelons in a tactical combat area. The need for real-time information distribution and the maintaining of concurrent data bases in a highly mobile, dynamic, highly dispersed battlefield becomes very complex.

The Army in the command and control subordinate subsystem (CCS^2) is presently investigating techniques to manage the data that are likely to be transferred in this tactical environment. The CCS^2 is an attempt to define an information management system that will support the required data transfer between systems supporting the five functional areas germane to the Army's mission.

To achieve the goals set for the cellular CP concept and the CCS^2, many difficult and challenging issues in data distribution, reliable data communications systems and information transfer between different Army networks must be investigated. Therefore, DARPA and the Army have conceived of, and are in the fourth phase of an ADDS testbed. The testbed is located in Fort Bragg, North Carolina, home of the Army XVIII Airborne Corps. Fort Bragg was selected for the testbed site so that ADDS experiments could be conducted at the corps level. The following sections briefly describe the testbed configuration, progress made in establishing the facility, and planning that has been made for conducting Packet Radio (ref. 1) (PR) and ADDS experiments during XVIII Airborne Corps field exercises.

Testbed Configuration

As presently configured, the testbed uses a combination of ARPA network* (ARPANET) (ref. 2) and PR resources. Figure 1 shows the global network in which various military organizations and the XVIII Airborne Corps uses the ARPANET as a communication medium and as a means for testbed access, observation, measurement, and participation.

To date, persons associated with the ADDS testbed at Forts Leavenworth, Monmouth, Monroe, and Gordon have been actively communicating with testbed personnel at Fort Bragg via the global network shown in Figure 1. In addition, persons who are members of the ADDS Steering and Working Group at

*The ARPANET is being used because it provides an example of a packet-switched long-haul network that is available today. This network is not intended for use as an operational system for the Army; it merely demonstrates what is possible with this type of technology.

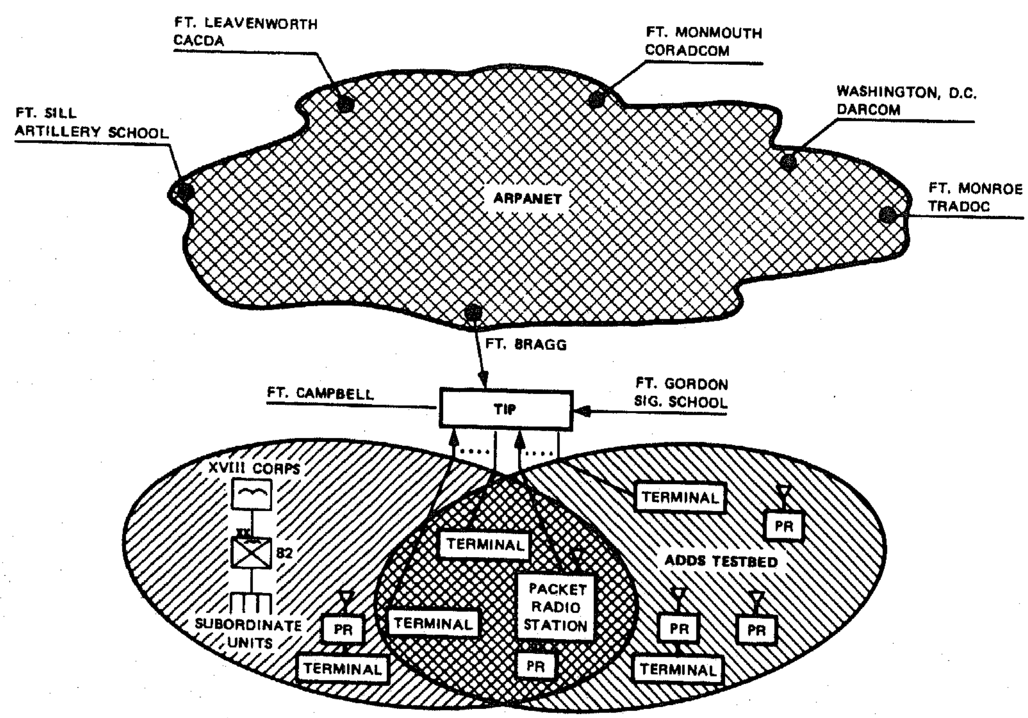

FIGURE 1 THE ADDS TEST BED

each of these military installations have been kept abreast of the progress in establishing the testbed via the ARPANET.

As shown in Figure 1, the global network relies upon use of the packet-switched ARPANET. The access nodes available to each of the organizations shown are ARPANET interface message processors (IMP) or terminal interface processors (TIP). To provide terminal access, the IMPs must first be attached to a host computer (which may be a terminal multiplexer), whereas the TIPs offer access through dial-up or dedicated phone lines. A TIP and C/30 IMP have been installed at Fort Bragg to provide access to the ARPANET by the on-site users. At the present time, the TIP supports up to 63 simultaneous users, each accessing the host computer at baud rates from 300 to 9600. The users typically experience total echo delays (the round trip time from when they strike a key on their terminal to when the response returns from the host computer) of about 300 to 500 ms. This delay includes that resulting from host processing of interactive users.

The first two phases of the Fort Bragg activity have involved only ARPANET resources. However, in FY80, a packet radio network (PRNET) was integrated into the testbed. These spread-spectrum PRs provide the basic communication system for C^3 activities. Specifically, the radio network fulfills two roles in the Fort Bragg testbed:

(1) Packet radio is used to assess the impact of an advanced, spread-spectrum, digital, data-distribution system on the Army's C^3 concepts and doctrine. In this role, the PR is a specific type of equipment that can satisfy several of the tactical data communication and distribution requirements of a highly mobile corps in the field.

(2) In its second role, packet radio provides broad-band channels for digital data relay within the testbed when other systems or distributed, survivable C^3 concepts (e.g., cellular CP) are investigated.

Packet Radio Network

The packet radio network is being developed by various contractors through support provided by the DARPA. The PRNET program is intended to investigate and to experiment with concepts in data distribution that will support the military. Specifically, the purpose underlying the development of the system is the dynamic allocation of system capacity and dynamic, automatic assignment of relays as required to support mobile and stationary users, particularly in a ground environment. The system continuously monitors radio connectivity topology, and based on this information, reassigns nodes (radios) for relaying purposes. Any radios can be used by the network as relaying resources, without interfering with the "user" attached to a radio.

At the present time, about 50 spread-spectrum* packet radios have been built and deployed to various testbeds for developing of the protocols (software algorithms) and concepts that support the automated network function. These testbeds provide "in-the-field" experimentation with users in the propagation and mobile environments described above.

The radios in these testbeds [experimental packet radios (EPR)] were intended for network protocol development and were not intended to investigate operations in an electronic warfare environment. However, DARPA has funded the development of several units intended for this environment. These radios, called upgraded packet radios (UPR), are being used to demonstrate that electronic counter-countermeasures for TRANSEC and antijamming can be supported in a radio built for automated network management and packet switching.† The more salient features of the testbed radios (i.e., the experimental units) are listed in Table 1. The brief packet radio description that follows is based on the experimental resources avail-

*See Table 1 for radio characteristics.

†DARPA and the Army have also begun the development of a low-cost packet radio (LPR). This unit will be housed in a 420-cubic-inch enclosure and will have the same basic characteristics as given in Table 1, except that the LPR will support pseudo-noise code changing per bit and forward error connection coding at various rates.

Table 1. EXPERIMENTAL PACKET RADIO CHARACTERISTICS

	Process	Characteristic
Radio	Frequency band	1710 to 1850 MHz
	Tuning	Digitally controlled synthesizer
	Occupied bandwidth	20 MHz (for 99.5% of radiated energy)
	Maximum output power	10 W
	Spread-spectrum technique	Direct sequence PN code
	Receiver threshold level	-99 dBm to -20 dBm (100 kbps) -93 dBm to -20 dBm (400 kbps)
Signal Processing	Data rate (dual)	100 (400) kbps
	Data modulation	DPSK
	Chip modulation	MSK (minimum shift keyed)
	Bit modulation	Differentially coherent
	Spread factor	128 (32)
	Processing gain	+21 dB (+15 dB)
	PN decoding	Surface acoustic wave matched filter

able in the San Francisco Bay Area development testbed. Kahn et al. (ref. 1) give additional information on PR technology.

The packet radio network is a packet-switched, broadcast network that provides area coverage simultaneously to fixed and mobile users. The common network element is the packet radio unit (PRU). Each PRU contains an omnidirectional antenna, an L-band spread-spectrum radio unit, and a digital unit. The microprocessor in the digital unit transmits and receives packets under control of the digital unit. In a stand-alone configuration, the PRU is termed a "repeater." If a subscriber is connected to the PRU, through a Terminal Interface Unit (TIU), the PR is termed "terminal" node. Connecting a specially programmed PDP-11/23 microcomputer to a PRU makes the combination a "station." The station contains processes for network routing, diagnostics, and measurements. The terminal interface unit contains software for end-to-end protocols, traffic sources, measurements, and terminal handlers for one or more data entry devices.

The packet radio receiver uses postdetection integration and actually takes advantage of the multipath often found in ground-based mobile operations. The integration extends over about one-third of a bit time, thereby trading some spread-spectrum time-capture potential for multipath resistance. The data rate is 400 kbps unless the noise or multipath environment becomes too severe, then a 100-kbps rate is automatically invoked.

For fail-safe operation and load sharing, protocols have been developed to permit multiple stations within the same network. A stationless-mode protocol is also being developed to permit reduced-capacity operations, should all stations become inoperative. Network management is exercised by the station through the use of intranet packets that are exchanged between all network elements. PRNET data packets vary in size up to a maximum of 2000 bits.

Packets are transported through the network on a store-and-forward basis using buffers within each PRU and a hop transport protocol between them. Packets for forwarding are broadcast from a node (PRU), but are selectively addressed to a single PR identified in the packet header. The relay process proceeds until the destination PRU is reached, at which time the packet is passed across an interface to an attached subscriber device (e.g., a video terminal). Positive acknowledgments (ACK) are required on a hop-by-hop (HBH) basis along the route. Each time an acknowledgment is not received for a packet (for any of several reasons), the PRU retransmits the packet. This process continues for a set number of retransmissions. Should this fail, a similar number of attempts are made to route the packet through alternative PRUs and, failing that, a new route is requested from the station and the packet is discarded to guard against deadlocks. Thus, the PRNET is potentially lossy. Because retransmissions can lead to duplicate packets, duplicate filtering is also performed in each PRU.

Network management includes procedures for initialization, routing, access control, and flow control. Initialization in the PRNET, including the addition or deletion of individual nodes, is automatic. The condition of all PRs and all links is frequently monitored, using special status reporting packets. These data, supplemented by PRU measurement data, are collected at the stations and form the basis for routing decisions. This type of information applies to mobile terminals as well. If connectivity from a mobile terminal to a repeater deteriorates, the mobile terminal is transferred to another repeater by a means transparent to the user.

In the current networks (composed of experimental packet radios), all users access the radio channel on the same frequency with the same spread-spectrum PN code. Access to the channel is controlled through protocols (called carrier-sense multiple access) to minimize packet "collisions;" allocation of system capacity to a user is based on dynamic demands made by the user (his packet offer rate).

In present generation PRNETs, allocation of all resources is on a demand basis. Hence, if a user must transfer large volumes of data continuously over long periods of time at high data rates, he limits other users' access to the channel. In its original inception, packet radio was based on the concept that user-to-user, user-to-computer, and computer-to-computer data typically exhibit high-peak-to-average (HPA) statistics. Hence, the protocols were optimized to support resource sharing for this type of data transfer.

However, while this is true for most users, some system resources must be assigned to support users whose data transfers do not have HPA statistics. Using the technology in the UPR that provides electronic counter-countermeasure facilities (specifically PN code changing for each bit of information transmitted), new protocols are being designed to support both types of users in a common PR network. These protocols will be implemented and tested when low-cost packet radios supporting PN code changing per bit become available.

An additional area that DARPA and the PR research community are actively pursuing is securing packet-switched networks. Subsystem designs have been completed and implementation has started. A secured PRNET at Fort Bragg, North Carolina is anticipated for calendar year 1984.

Tactical Testbed Objective

The primary objective of the ADDS Testbed Experiment is to show how state-of-the-art technologies in the areas of packet-switched, spread-spectrum, mobile radio and advanced information processing techniques can support the real-time information (data) flow and the distributed communication architecture that the Army requires so that it can survive and execute its mission on the modern battlefield successfully.

This primary objective is a composite of a set of objectives developed by the ADDS working group for the testbed. This set of objectives is:

(1) Evaluate developing technology in distributed communications such as PR, in a military tactical environment.

(2) Demonstrate the integration of emerging technology into ongoing system development, identifying early in the development cycle

the impact on system requirements and capabilities.

(3) Develop and experiment with new and modified doctrinal concepts using emerging technology.

(4) Evaluate impact of new technology and doctrine on organizational structures.

(5) Investigate and evaluate methods for improving the C^3 operational readiness of the tactical Army.

To determine what information (data) is required by the Commander in a tactical environment for C^2 of his assets, two months were spent meeting with members of the major staff elements of the XVIII Airborne Corps and the 82nd Airborne Division. As part of our discussions, we asked the Corps and Division G2 (Intelligence), G3 (Operations), and G4 (Logistics) to establish the priority of those reports (issued in the field), according to their importance for achieving the primary objective of the testbed.

To limit the scope of the effort required to implement an experimental, computer-based, PR supported, tactical reporting system (TRS), six tactical reports will be automated. They include: intelligence summary, spot intelligence report, operational situation report, unit location update, logistical status report, and battle loss report.

Following our discussions with the Corps, it became evident that if the experiments were to have any validity, a vertical cut of the information flow from the brigade level (or even battalion level) to the corps level must be supported in a corps field exercise. Based on this observation, we have developed appropriate deployment strategics of PRs in a corps exercise. In this deployment, four users at each echelon are multiplexed onto one PR via a TIU.

The Army's problem of supporting tactical information management and distributed, survivable C^3 architectures, however, is much more complex than merely automating a few fixed-format reports. Hence, a TRS is being developed that will include automated information transfer across communication or functional Army networks (i.e., intranetwork and internetwork information transfer). The tactical reporting system supports user-to-computer and computer-to-computer data exchanges. It automatically generates (as required) distributed, replicated data bases. Thus, the TRS architecture will support near-term concept and doctrine evaluation for CCS^2 and cellular CPS, while supporting the specific C^2 reporting required by the XVIII Airborne Corps.

Program Plan

To achieve the testbed objective, a multiple-phase program was designed that gradually introduces advanced communication and computer technologies to a user population that, as a group, has had little or no exposure to these technologies. At the present time, a four-phase program is being executed.

During the first phase, twenty-three computer terminals were deployed to the XVIII Airborne Corps members participating in the experiment. Directories on the "D" computer at Information Sciences Institute (ISI) were established for these users, and they were trained on how to use several of the resources available on that computer.

This initial effort gave the new users an understanding of the manner in which computer networking technology as embodied in the ARPANET (real-time, interactive computer support, data-base management, and electronic mail) could be used as aids to make the work easier. Although support of these daily activities is not the primary goal of the testbed, we discovered early in the program that if the user is to become proficient with and motivated to use the technologies being provided, he must feel that the benefit he receives is worth the effort he must expend in learning them. Hence, the testbed implementor has been concerned not only with creating a TRS, but also with supporting (and thereby motivating) the user in his daily activities. This approach has, to date, been very successful. Users have become comfortable with the on-line, interactive, computer environment that has been established at Fort Bragg. The acceptance of this technology is the stepping-stone that has led the users to participate in the C^3 ADDS/PR experiments being executed during Phase IV of the testbed.

During Phases II and III of the program, the size of the testbed was increased from twenty-three computer terminal sites to forty sites. In addition, a total of about 800 users were trained, application software for several specific requirements was delivered, software to monitor the use of the system by the Corps was developed, and a PRNET was installed at Fort Bragg. This PRNET permits the Corps to retain the C^2 automation developed on the testbed computer resources, while the Corps is "in the field and on the move."

In Phase IV of the experiment, the testbed concentrated on supporting the Corps C^3 requirements during one of their field training exercises (FTX). Although presently the assets are insufficient (e.g., radios) to support all communication needlines for the Corps, the allocation that has been devised will permit us to assess the impact of automated reporting systems, ADDS, and distributed C^2 systems on the success of the Corps in the performance of its mission in an FTX.

Tactical Reporting System

As described above, a military requirement is emerging for an automated TRS at corps level and below. The centralization and bottleneck of existing military message centers creates message delay and the risk of message loss. When completed, TRS will provide the Army with the opportunity to begin experimenting with distributed, survivable C^2 architectures. Specifically, it is designed to support concept development in:

- Redundant C^2 data-base architectures
- Multiprocessor C^2 architectures
- Distributed command-post architectures
- Mobile C^2 experiments
- Multiple network/internetwork C^2 architectures.

The overall architecture of TRS is much broader, however, because it supports information transfer and controlled access for any type of data in both a network and internetwork environment.

System Design. A tactical reporting system must satisfy military organizational needs, goals, and constraints. High-level issues that have been addressed in the TRS design include:

- Communications subnetwork architecture and protocols
- Data-base distribution and control
- Data-base processing and relationships
- Military organizational hierarchy and information protection
- Recovery and self-recognition of the system.

In TRS, tactical data processing elements (hosts) may be geographically separated and are not required to operate within the same communications subnetwork. This is accomplished through the use of DoD standard network protocols called transmission control protocol (TCP) and internetwork protocols (IP); both are discussed in detail in Postel (ref. 3).

In TRS, the data-base architecture creates a replicated distributed system. The TRS implementors are investigating data-base techniques that result in replicated systems with syntactical and semantic integrity. The former implies that all transactions against the data bases arrive at each node in the same order. Semantic integrity implies that after the "N^{th}" transaction against each replicate data base, the data content of each base is the same as all others. Semantic integrity requires that a particular transaction either be processed only once at all nodes or at none.

In the past, typical computer-based message systems were inefficient in their use of communication and storage resources because, although one message may have many addressees all on the same host, each addressee received his own copy. For TRS, this situation has been improved by developing a mechanism whereby only one military message data base is on a given machine and access to messages within the data base is governed by appropriate "chain-of-command" authority within the military or organizational structure. The access privileges for each authorized user of TRS are contained in an automated hierarchy reporting structure (HRS) that has been integrated into the reporting system.

Hierarchical Reporting Structure. The hierarchical reporting structure (HRS) is the element of TRS that provides control for access and delivery of the tactical reports. Unlike ordinary message systems, tactical reports have predefined source and destination entities and strict rules governing access rights to the message contents. The HRS provides the addressing information for a report, preventing the user from creating his own arbitrary addresses, while at the same time freeing the user from address preparation. The HRS, when queried by the various reporting programs, determines which users have access to which reports. Furthermore, the hierarchical reporting structure manages alterations in the reporting flow, providing immediate response to changes in the military hierarchy.

Tactical reports have three types of addresses. The source address is the name of the report originator; the unit that fields the report. The source address is the "from" entry in typical tactical reports. The destination address is the name of the recipient of the report, and is the "To" entry in typical tactical reports. The "info" address is the name of the unit that can examine the report for informational reasons, although not the formal report recipient.

The HRS uses a modified rooted-tree concept to model the reporting flow. Each node in the tree represents a unit that prepares or receives tactical reports or both. If two nodes are connected, the one closest to the root is the destination of the report, and the node farthest from the root is the source of the report. The Corps is the top node, or root of the tree. Coming from the root are two immediate subordinate nodes, the 82nd Airborne Division and COSCOM. Because the Corps node is closer to the root than the other nodes, it is the destination of any reports sourced by its immediate subordinate nodes. From the 82nd Airborne Division node the tree branches further to brigade DISCOM, and battalion nodes.

The hierarchical reporting structure contains a variety of information relevant to each node. For example, a node has a name used for human interaction (e.g., XVIII Corps) and a node identifier used for machine interaction. Each node has a set of subordinate nodes (nodes further from the root), and a set of superior nodes (nodes closer to the root). A node has certain functional entities; these may vary amongst the TRS reports. Thus, for each report, and at each node, HRS maintains and automatically uses sets of the following information:

(1) Action Address--The directories that can file reports for the specified report at the specified node. Users logged into or connected to these directories receive notification when a report is filed that contains the specific node as the destination address.

(2) Info Address--The directories that can examine reports filed, received, or "info'ed" to the specified node.

(3) Outgoing Info Address--The nodes that can examine reports filed by the specified node.

(4) Forward to Address--The node to be used in place of the specified node should that node be referenced as a destination.

The HRS also supports a multiple-echelon reporting structure where the reports can be simultaneously provided to units in the chain of command superior to the reporting unit. This capability is done by switches designed into the software. If so desired, these switches can be turned "on" to permit evaluation of multiple-echelon reporting by the Army.

Although the tactical reporting system is in its early stages of development, significant progress has been made toward providing the resources necessary to support concept development and investigation for distributed C^3 for the Army. Through its design, considerable flexibility has been built into TRS. For example, the report formats supported by the system are contained within a module. Thus, if concept development or evaluation of JINTACS reports is desired, the appropriate report formats for this system can be efficiently built into TRS. Additional details on TRS can be found in Frankel et al. (ref. 4) and details on the ADDS Testbed can be found in the reports for SRI International Project 1056 (refs. 5-8).

The First Tactical Packet Radio Field Exercise

The initial effort at moving the Fort Bragg PRNET out of garrison and into a field environment was scheduled concurrently with a Corps field exercise. Because the PRNET is not yet secured, deployment restrictions were introduced that precluded active involvement of the radios in the scenario. Nonetheless, efforts to deploy the hardware in the field continued with a view toward at least a reduced participation in the Corps exercise.

The Corps agreed to allow the PRNET to be in the field during the exercise "predeployment" period. Following this agreement by the Corps, early meetings were held with representatives of the 35th Signal Brigade to define support needed. A platoon of signal troops from the 327th Signal Battalion was assigned to give direct support to the PRNET field deployment.

Movement of equipment to the field began on 19 March 1980. The three repeaters placed in the field each had line-of-sight connectivity to the garrison repeater on Womack Army Hospital. Their distance from Womack ranged from 3 km to 7 km. The repeater sites were Pike Field (Figure 2), Pioneer Airfield, and Monroe Mountain; all located at Fort Bragg. Two user (terminal) sites were established at 7 km and 11 km from the Womack repeater. One user site, Lamont Road (Figure 3), was used by the 35th Signal Brigade for demonstration and routine operation during the deployment and during the field experiments. The second user site was at Latham Airfield (Figure 4), the farthest site from the Womack repeater. The Latham Airfield site had two terminals, which were manned by the 327th Signal Battalion; these latter two terminals were also used for demonstration and experimentation by contractor personnel.

Equipment at each repeater site consisted of an antenna tower; heliax antenna cable attached to the PR antenna on top of the tower; an EPR housed in a minishelter; and two 12-V, sealed, lead-acid automobile batteries enclosed in a plywood box. The two batteries, in series, provided 24-V, dc power for operation of the repeater EPR.

As part of the deployment of the PRNET, preliminary experimentation was conducted. At the time that the experimentation began, most of the garrison radios had been moved to the field. For this reason, the PRNET at that point consisted only of the five field radios, the Womack repeater, the station PR, the network operations and monitor PR, and a PR without an attached TIU at one garrison site (the 20th Engineer Brigade). Once the field sites were deployed, PRNET connectivity, as seen by the PR station, was recorded. All field sites had mutual connectivity except for Latham Airfield, which had connectivity only with the station PR, Womack repeater, Monroe Mountain repeater, and the terminal site at Lamont Road (it did not have connectivity with the field repeaters at Pike Field or Pioneer Airfield). Using this network configuration, various experiments were performed. Figure 5 shows the network deployment.

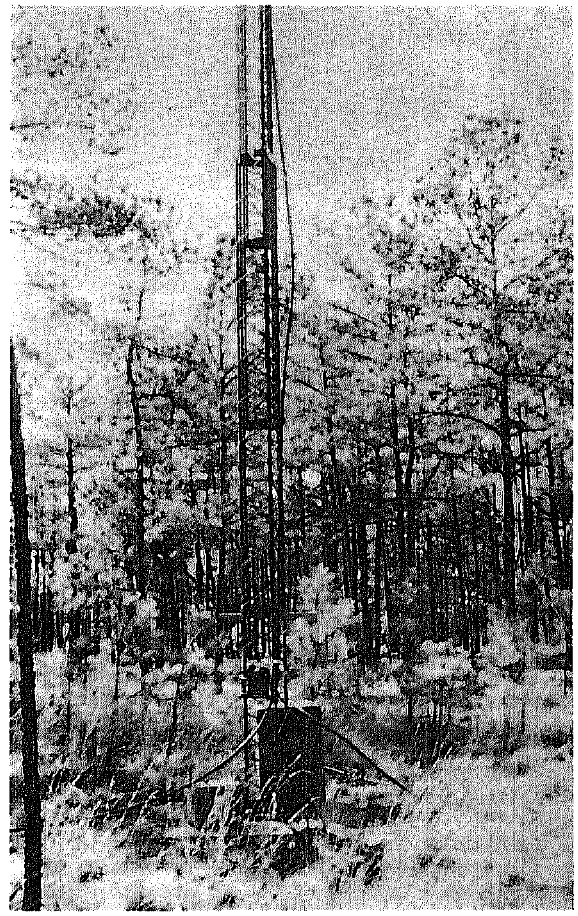

FIGURE 2 PIKE FIELD INSTALLATION

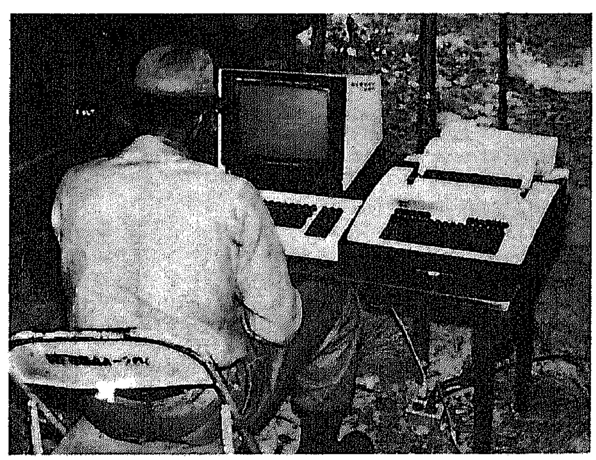

FIGURE 3 PRNET USER AT LAMONT ROAD SITE

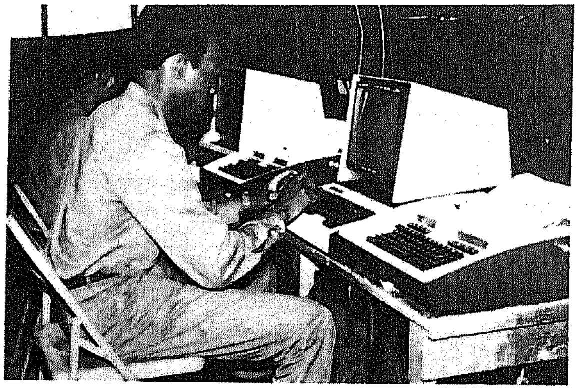

FIGURE 4 PRNET USER AT LATHAM AIRFIELD

The prime measurement tool for determining user-visible throughput was the program, PTIME, running on ISID. PTIME sends a standard-length text file to the user's terminal, and records the total time and effective bit rate for this activity. Data traveling the path from the user terminal on the PRNET to the ISID ARPANET host go through a number of network elements, each capable of adding to the total delay seen by the user. These elements are: TIU, PRNET, station, gateway, ARPANET, ISID computer, and TCP software processes in both the TIU and ISID. PTIME, of course, can only roughly measure the total result, and is quite susceptible to variations in the load average on the ISID computer.

The results of the various experiments have been reported to the Army and development committees. The results were typical of the in-garrison PRNET, and were as expected. User acceptance of the technology (because of the data-distribution capability it provided) was overwhelming. It is clear from this exercise that an automated, reliable, self-managing, distributed data communications system is a necessity for enhanced C^2.

STRATEGIC C^3 TESTBED*

Systems to enable positive control of the strategic forces by the National Command Authority (NCA) have been carefully designed and exercised in a friendly, neutral environment. Sophisticated ground-based computer support has been structured to aid the C^2 activities of the NCA as well as those of the strategic CINCs; however, there is a widely shared concern regarding the survivability of these systems in the event of a nuclear exchange. The effects of a nuclear attack will be greater than the immediate physical damage. The potentially degrading effects of a nuclear burst on electronic equipment and radio propagation are expected to be significant and, added to the general confusion, will hamper C^2 activities.

In addition to the primary need for systems that can support an immediate U.S. reponse to an initial attack, there is a longer-term requirement for C^2 of surviving forces in response to a protracted nuclear war. C^3 must survive and offer sufficient flexibility to identify, reconstitute, and employ surviving assets.

Technologies must be developed and applied in the context of national requirements; however, a more directed focus is necessary to demonstrate specific capabilities. The Strategic Air Command (SAC) has a global mission that includes the requirement for C^2 of two legs of the strategic triad. Realizing the need for survivable C^2, SAC

*This section is an excerpt from Druffel and Frankel (ref. 9).

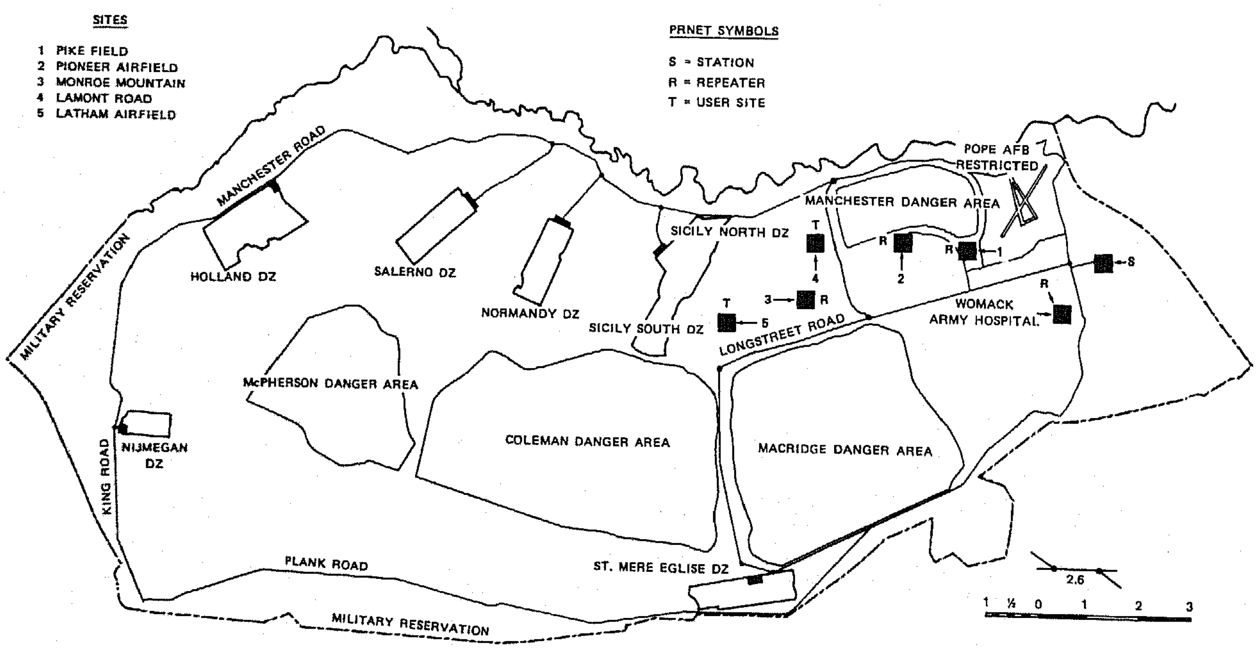

FIGURE 5 FIRST PR DEPLOYMENT EXERCISE

has deployed the airborne command post (ABNCP), which will serve the C^2 function in the event that the more sophisticated fixed facilities are destroyed. In response to the need to continue C^2 for the duration of a protracted nuclear exchange, SAC is developing a new ground-based, mobile command center called the Headquarters Emergency Relocation Team (HERT). Such teams would be deployed upon strategic warning to provide backup C^2. Although still an evolving concept, the HERT is representative of SAC's efforts to develop a surviving C^2 facility.

In view of this increasing concern to ensure survivable C^3, DARPA, SAC, and the Defense Communications Agency (DCA) have agreed to establish a testbed to conduct experiments that focus on C^3 support to the HERT and ABNCP.

Testbed Objective

The objectives of the Strategic C^3 Testbed are: (a) to demonstrate the feasibility of using advanced technologies in information processing and communications to support a system architecture that can provide survivable trans- and post-attack C^2; (b) to develop the functional and performance requirements for an operational system; and (c) to evolve the preliminary doctrine for the employment of such a system. The program focuses on SAC's mission to reconstitute surviving strategic forces and is creating an experimental system through which advancing technologies such as packet switching, end-to-end network security, and distributed knowledge and data bases may be evaluated as a means for supporting C^3 for SAC.

Testbed Scenario

In a prehostility environment, the present SAC C^3 system relies on ground-based strategic data bases. Information is transferred to these data bases by conventional communication systems such as UHF radio, commercial common-carrier systems, and military telephone and land-line data-transmission systems. Furthermore, SAC's command and control of its assets is also supported via this collection of communication hardware.

A question arises about the availability of these communication resources during trans- and post-attack environments. We speculate that under such conditions many of these systems will be at best fragmented; i.e., partitioned in such a way that islands of communication and data base resources exist. In addition, we envision that groups of people will require access to these data bases to carry out their mission effectively.

At present, we are unaware of any system that permits the reconstitution of the resources available to these islands into a unified C^3 structure. This realization has, in fact, led SAC to recently develop the concept of the HERT. The mission of this cadre of people is the establishment of a ground command post that will attempt to reestablish communication with airborne resources (e.g., data bases, personnel, and the like) and surviving ground-based resources.

Although the Headquarters Emergency Relocation Team is a first step toward achieving the goal of providing enduring C^2, we believe that its effectiveness can be greatly enhanced if the advanced technologies being developed by IPTO are integrated into its development. For example, consider the following scenario. (Although this scenario may appear futuristic, many of the technologies it presupposes are under development and should become available during the next decade.)

We envision a backbone communication system that can transfer high-speed, nearly error-free data. This system (packet radio) would be deployed on SAC aircraft, to the HERT, and at many strategic locations on the ground. These radios will be networked providing a means of rapid transfer of information between ground-based and airborne strategic data bases. For survivability, all data bases will be redundantly distributed, and will be supported by special-purpose, distributed database software that ensures that they contain updated, reliable information. Furthermore, the radios will contain software permitting them to reestablish dynamically communication between airborne users, and to reestablish communication with surviving "islands" that would have valuable strategic resources. This concept is shown in Figure 6. This automated network management includes the reconstitution of any communication assets that survive the attack (e.g., satellites and ground-based systems that have been augmented to operate in a packet-switched environment).

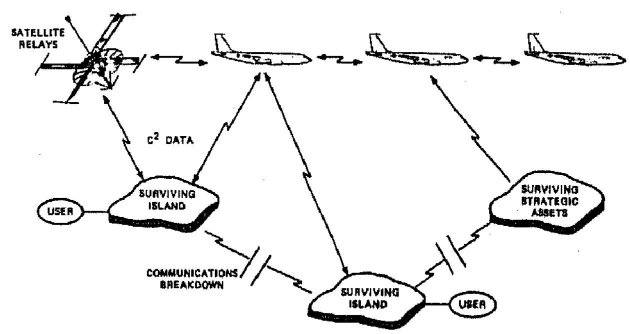

FIGURE 6 SAC C^3 CONCEPT

An important aspect of this scenario is that resources and the updating of data bases will be reconstituted in real time and automatically. Automation is one of the keys to the enhancement of present C^3 systems. To date, all concepts have relied on human, labor-intensive activities for data acquisition and communication reconstitution (e.g., airborne data-base updates and the airborne search for surviving communication channels). Because of the immense amount of effort involved in these activities, we are told that present systems provide little time for execution of C^2.

In the scenario, we also envision that: (1) all SAC aircraft can transfer data to any other aircraft within an approximately 250-mile line-of-sight (LOS) radius; (2) that all aircraft can receive and transmit data to any ground entry point within a 250-mile LOS from the aircraft; and (3) that each airborne radio can act as an automatic relay, storing and forwarding data from any source to any destination that has the appropriate communication hardware.

Utilizing this backbone data-communication network in the trans- and post-attack environment, a commander will have access to significant amounts of strategic information; he will also have communication with his surviving forces. This connectivity and access to information will permit him to perform his C^2 function more effectively. The goals of the SAC C^3 experiment are directed toward achieving this scenario during the lifetime of the testbed.

Experiment Structure

In the context of the experiment objective, specific technologies will be demonstrated in support of SAC C^3 requirements. An experimental system will be established through which SAC may evaluate these technologies and evolve a doctrine for their employment.

The experimental nature of the program will require the use of brassboard equipment and example systems such as the ARPANET and spread-spectrum PR. Although this equipment will be demonstrated in operational environments and may find limited use in fulfilling interim requirements, they are experimental and transitional. The intent is to demonstrate concept feasibility and facilitate technology transfer to an operational command. The program will address vulnerability issues and system design considerations that will pave the way for the acquisition of an enhanced capability.

The program consists of three major phases: (a) airborne packet radio network; (b) distributed C^2 software; and (c) communications reconstitution.

Airborne Packet Network. The airborne packet network is to demonstrate the feasibility of implementing a survivable, packet-switched internetwork with the following capabilities:

- Reliable end-to-end data exchange with no requirement for manual intervention at intermediate (relay) nodes.
- Dynamic network reconfiguration to support mobile nodes or adapt to node failure.
- A PR network throughput on the order of 20 kbps.
- Air-to-air, air-to-ground, ground-to-air, ground-to-ground, ground-to-air-to-ground, and so forth; data links.
- End-to-end communication security.

This system is to provide flexible access to distributed ground and airborne computer facilities and data bases. The concept is to enable a surviving command team to access not only its own data bases, but also other surviving assets in the network. This concept is based on the conviction that flexible C^2 requires access to critical data and computing resources.

The experimental system will be based on the existing ARPANET as a sample terrestrial network and on a PRNET similar to that described above. Ground entry points with gateways to other networks, primarily ARPANET and possibly the Defense Digital Network (DDN), will be used to demonstrate Internet capabilities.

Distributed C^2 Software. The goal of the distributed C^2 software phase is to develop software representative of that which can support SAC's distributed C^2 requirements. Although SAC has a sophisticated computer-oriented C^2 system in its primary fixed facility, its emergency C^2 facilities, on the other hand, depend largely on manual systems. SAC has developed an airborne computer facility that provides a limited local data base and a modest level of automation support for C^2 activities. Successful development of an airborne packet network introduces an expanded dimension to the use of automation. This network will support the sharing of airborne C^2 resources, and the airborne links to ground and terrestrial networks will allow access to surviving, fixed resources as well as provide for connectivity among otherwise isolated terrestrial resources. Likewise, the continued progress in miniaturization of electronic circuitry makes investigating the use of more powerful automation facilities on an airborne platform reasonable, paving the way for computer assistance in the conduct of C^2. Consequently, considering the replication of, as well as the sharing of, data bases is feasible.

Three types of software activity are being undertaken for the testbed: (a) state-of-the-art software engineering; (b) transfer of maturing software techniques; and (c) research into new techniques for support of C^2 functions.

Communications Reconstitution. The concept for reconstitution of surviving communication assets into a usable communication network for C^2 is predicated upon two assumptions. First, islands (enclaves) will survive that contain dissimilar communication assets; for example, the assets will support different communication bandwidths, different transmission media, and the like. Second, some surviving islands will contain SAC command personnel and strategic data bases. For effective C^2, these surviving islands must be able to communicate with each other and provide command access to data (airborne or ground-based).

The reconstitution of surviving, dissimilar, communication resources will require that specific internetting technology be developed in anticipation of the need. This technology must support reliable end-to-end data transfer and provide (via appropriate system design and protocols) a mechanism for reconstituting the surviving communication assets into a networked system to support C^3 and information exchange. The technology will provide the basis for demonstrating that reconstitution of packet-switched systems can be accomplished using airborne packet networks as automatic relays. During Phase III of the testbed, experiments will be carried out with the ARPANET, possibly DDN, and several PRNET now operating in CONUS. These experiments will demonstrate that an ABNPN can be used to reconstitute a fragmented ARPANET. The ABNPN will also be used to interconnect (reconstitute) DDN to the ARPANET. These experiments will verify that a communication network-management system can be designed that will automatically reconstitute "surviving" packet-switched communication assets.

If current research efforts are fruitful, nodes of a highly distributed, survivable network can be integrated into the SAC C^3 testbed. Using these nodes, experiments would be conducted to demonstrate that a survivable communications network can be developed that uses (through internetting) available commercial and military communication assets, thereby extending the usefulness of an ABNPN.

At the conclusion of the program, a major exercise will be conducted with SAC, in which the entire capabilities of the SAC C^3 testbed are used. This exercise will demonstrate reconstitution of communications (both airborne and ground-based); it will use distributed data-base technology and C^2 software specially developed for SAC during Phase II of the program. This exercise is intended to demonstrate that technology exists for automating SAC's C^3 requirements. If this effort is successful, it will provide the foundation for the development of a fully automated, highly survivable C^3 system.

Testbed Status

During the past eight months significant progress has been made in the testbed. Many experiments have been conducted, and the establishment of the testbed and the integration of resources necessary to fulfill the testbed objectives has begun. A particularly interesting experiment is discussed below; Fair et al. (ref. 10) discuss other experiments that have been performed.

Airborne Relay Experiment. The experiment, conducted during December 1980, was to:

- Demonstrate the feasibility of "automatically" providing radio connectivity between "isolated" ground stations using an automatic, airborne PR relay.
- Investigate the effects of Doppler shift on PRNET performance.
- Obtain data on packet error rates for both the "hidden" terminal and airborne PR.

The experiment proceeded as follows: A mobile van, containing a PR and a "user terminal," was driven about 30 miles south of Menlo Park, California, over a mountain range toward Santa Cruz, California, to a location from which there is no connectivity with the Bay Area PRNET. The SRI aircraft was flown southeast of San Jose, California, at approximately 10,000 ft.*

The data that have been analyzed show that the aircraft acted as an effective relay for the hidden terminal at all times the aircraft was within LOS range of the PRNET and the van. In fact, the van was automatically made a member of the network when the relay aircraft came into LOS. No "user" intervention was required to establish the links between the van and the ground-based PRNET; these reliable "data links" were transparently established by the protocols and automated network management software that have been integrated into the PR.

Airborne Packet Radio Network Power Requirements/Frequency Allocation. If the airborne PRNET is intended to provide a mechanism for automated reconstitution of ground-based packet-switched networks, the radios must have maximum communication range when they are deployed on platforms that typically fly from 30,000 to 35,000 ft. At this altitude, the maximum aircraft-to-ground LOS is about 250 miles. Now, the RF transmitter power needed to communicate over a 250-mile LOS link is a function of antenna characteristics and the radiated frequency. The power required (P_t) can be calculated using the familiar range equation:

$$P_t = \left(\frac{4\pi R}{\lambda}\right)^2 \frac{P_r}{G_t G_r} \quad (1)$$

where:

P_r = Received power (same units as P_t)

G_t = Transmitter antenna gain

G_r = Receiver antenna gain

λ = Wavelength, in meters

R = Range, in meters.

For a given application, the gains of the antennas on both ends of the link must be defined and the minimum received power necessary for adequate communications (threshold level) must be specified. This would be all the information that would be necessary to calculate the required transmitter power to establish the link if the system were not subject to propagation and implementation uncertainties.

In the SAC scenario, however, the system is subject to these uncertainties. Therefore, eq. 1 should be modified to allow for variations in the transmission path by adding an extra term (margin) to the equation, which then becomes:

$$P_t = \left(\frac{4\pi R}{\lambda}\right)^2 \frac{P_r M}{G_t G_r} \quad (2)$$

where M = link margin.

In the case of air-ground communications, the margin is necessary to compensate for reflections from the aircraft structure that cause nulls in the airborne antenna pattern, and for link degradation resulting from multipath signal fading. Other factors that are normally lumped into the margin term are cable losses, system implementation uncertainties, and atmospheric propagation effects. If the system must have reliable communications 99.99 percent of the time, good engineering practice will allow a margin of 40 dB, whereas if a reliability of 90 percent is acceptable, a margin of only 10 dB would suffice (ref. 12).

This difference of 40 dB versus 10 dB in the values of margin (and hence required transmitter power) greatly increases the cost of the system. Therefore, engineering compromises must be made. For the system design discussions to follow, we shall assume a value of 10 dB.

Because the antenna characteristics for the SAC application were not defined at the outset, some assumptions about antenna gains must also be made. The link with the most constrained power budget will be the aircraft-to-aircraft link because the size of the antenna that can be mounted (and flown safely) on the high-performance ABNCP is limited. Typical structures used on aircraft of this type

*Complete details on this experiment are in ref. 11.

are blade antennas that possess a monopole over a finite-ground-plane radiation pattern. Their patterns possess a maximum gain above (or below) the horizon on the order of 5 to 6 dBi with a gain in the direction of the horizon of about 0 dBi. Ideally, the maximum antenna gain should occur at elevation angles corresponding to the maximum range (near the horizon), with proportionally lower gain at angles where the range is less. At maximum range, the elevation angle between the aircraft and the ground (or another aircraft at low elevation) is only a few degrees. Hence, an antenna gain of 0 dBi (assuming monopole structures) is appropriate for the transmitter power calculations that follow.

Using values of 10 (10 dB) for M, 1 for G_t and G_r (0 dBi), 400 km (250 miles) for R, and 5×10^{-13} W for P_r (the -93 dBm, 400-kbit/s threshold of EPRs), eq. 2 can be solved for the values of P_t required to meet this threshold for any frequency. Figure 7 shows the values of P_t obtained for the frequency range of interest. Approximately 1 kW of RF power is required at a frequency of 800 MHz and greater than 5 kW is required at 1850 MHz! Assuming a nominal transmitter efficiency of 25 percent, the input power that would be required for each airborne PR installation would be 20 kW when operating at the latter frequency.

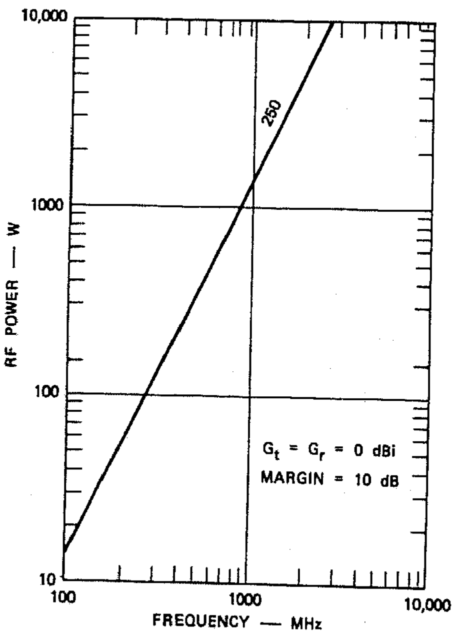

FIGURE 7 RF POWER REQUIREMENTS

Based on our recent market survey, the cost data for obtaining RF power amplifiers to satisfy the communication requirements, shown in Figure 7, are shown in Figure 8. Based on these cost data, a survey of RF systems aboard EC-135 aircraft, and frequency spectrum utilization, a frequency allocation in the 902 to 928 MHz band has been tentatively selected for the SAC airborne PRNET.

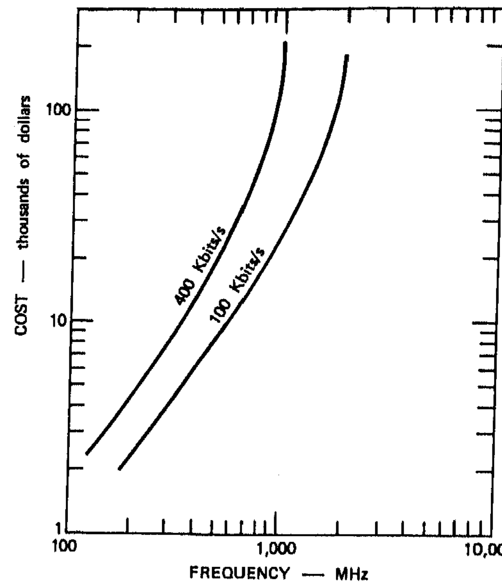

FIGURE 8 POWER AMPLIFIER COST

CONCLUSION

This paper has described two testbed programs (one oriented toward tactical users, the other toward strategic) that are using emerging, advanced technologies in support of concept development and evaluation in distributed C^3. The technologies being integrated into the testbed address not only distributed, survivable communications for C^2, but also the technologies that permit the effective use by commanders of information transferred over these communication resources. Advanced technologies are being integrated and experimented with as a means for supporting the entire military C^3 problem.

These technologies include: automated tactical reporting systems, investigation of automated man-machine interfaces, communications (data distribution) in a network and internetwork environment, automated display and analysis of data, and techniques for automatically and redundantly sending information in data bases. The integration of these technologies, from inputs obtained from real-world users, should provide the basis for the development and evaluation of concepts and systems for distributed C^3. Expectations are that the testbeds will ultimately lead to the definition of integrated military distributed C^3 architectures that will permit a commander to execute his mission in the "battlefield of the future" more effectively.

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