Satellite-Enhanced Personal Communications Experiments

Deborah S. Pinck & Loretta H. long
Jet Propulsion Laboratory,
California Institute of Technology, M/S 161-241,
4800 Oak Grove Drive, Pasadena,CA91109
Phone: +1-818-354-8041, Fax: +1-818-393-4643,
e-mail: pinck@zorba.jpl.nasa.gov

Anthony J. McAuley & Michael Kramer
Bellcore(MRE 2N263)
445 South Street, Morristown, NJ 07960-4698
Phone: +1-201 -829-4698, Fax: +1-201-829-2504,
e-mail: mcauley@bellcore.com

Abstract

As an initial step in exploring the opportunities afforded by the merging of satellite and terrestrial networks, Bellcore and JPL conducted several experiments utilizing Bellcore's experimental Personal Communications System, NASA's Advanced Communications Technology Satellite (ACTS) and JPL's ACTS Mobile Terminal. These experiments provided valuable information on the applications, interfaces, and protocols needed for seamless integration of satellite and terrestrial networks.

1 Introduction

Users of future generation wireless information services will have diverse needs for voice, data, and potentially even video communications in a wide variety of circumstances. For users in dense, inner-city areas, low power PCS should be ideal. Vehicular-based users traveling at high speeds will need high power cellular networks. Packet data networks provide an excellent solution for users requiring occasional small messages, while circuit switched networks provide more economical solutions for larger messages, For users in remote or inaccessible locations, or for applications that are broadcast over a wide area, a satellite network would be the best choice. To provide ubiquitous personal communications service, it is necessary to integrate all these networks into one seamless internetwork, using the strength of each network.

As an initial step in exploring the opportunities afforded by merging various networks, Bellcore and JPL conducted a series of experiments [1] to demonstrate the joint use of satellites and terrestrial networks in the delivery of personal communications services.

This paper describes results from several field trials conducted during August 1994 and January 1995 in Los Angeles, CA and Morristown, NJ. During these trials, applications communicated over various combinations of networks including satellite, wireless packet data, the wired Internet, and the wired Public Switched Telecommunications Network. Section 2 describes the experiments, Section 3 presents the results, and Section 4 provides an analysis of the data collected.

2 Experiment Description

This section describes the satellite-enhanced personal communications experiments. The goals of the experiments are listed first, followed by a description of the experiment configuration. Next, the satellite and terrestrial protocols are explained, and lastly, each of the applications is described.

2.1 Experiment Goals

The experiment goals fell into three categories: a) demonstrate the delivery of personal communications applications via satellite, b) demonstrate interoperability of satellite and terrestrial networks, and c) evaluate protocol mechanisms and parameters for data applications communicating over wireless links. This work is important because:

- Applications currently planned for terrestrial PCS need to be demonstrated on the satellite network to determine their behavior, and consequently their commercial viability, in a satellite-enhanced personal communications network.
- Various terrestrial wireless networks, including packet data and cellular networks, need to be integrated with the satellite network to evaluate overall end-to-end system performance.
- The protocol mechanisms (e.g., selective vs. cumulative acknowledgments) and parameters (e.g., packet size) developed for terrestrial PCS need to be tested and optimized for use over satellite and

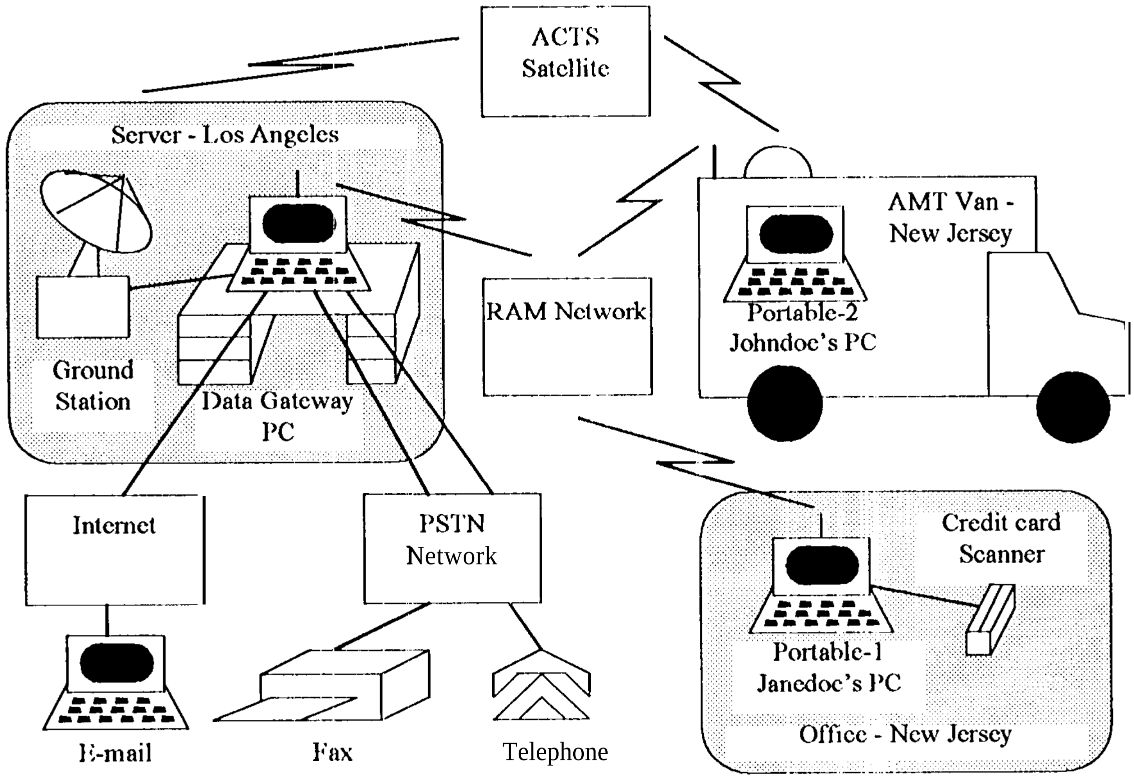

Figure 1 Satellite-enhanced PCS Experimental Setup

integrated terrestrial/satellite networks.

2•2 Experiment Conjuration

These experiments utilized Bellcore's Experimental Personal Communications System (BEPCS), NASA's Advanced Communications Technology Satellite (ACTS), and JPL's ACTS Mobile Terminal (AMT). Figure 1 shows the experimental configuration involved in this series of experiments.

BEPCS consists of a Data Gateway PC located at the satellite ground station, the portable PCS (one belonging to the hypothetical Johndoe and the other belonging to the hypothetical Janedoe), the credit card scanner, the prototype application software (see 2*4), and an experiment al transport protocol TPE (see 2•3). All the BEPCS hardware uses standard commercial components with custom applications and protocols. The Data Gateway has multiple serial ports allowing it to route all five connections simultaneously: Satellite, RAM, Internet, PSTN to any fax, and PSTN to any telephone. (RAM is a wireless packet data network.) The portable PCS, however, have only a single serial port, so during internetworking experiments the RAM modem was directly connected to the satellite equipment, bypassing Johndoe's PC.

ACTS is an experimental K/Ka-band satellite developed by Martin Marietta Astro Space under contract to NASA. The satellite, launched into geostationary orbit at 100 degrees west longitude in September 1993, operates in a virtually untapped frequency spectrum in the K- (20 GHz) and Ka-bands (30 GHz).

The AMT [2] is a proof-of-concept K/Ka-band mobile communications terminal intended to demonstrate the system techniques and high risk technologies needed to accelerate the commercial use of land-mobile systems at K/Ka-band. One such technique is the ability to integrate the mobile terminal for satellite communications with terrestrial personal communications equipment, To support this integration, the AMT Terminal Controller provides a digital interface between the portable PCs and the AMT. The data signal is then up/downconverted to the satellite frequencies for transmission over the K/Ka-band channel. The baseline AMT can support up to 128 kbps full duplex communications, for this experiment, a 9.6 kbps link is used. A sophisticated Data Acquisition System (DAS) has been developed to provide real-time monitoring and data collection for the AMT system. For land-mobile experiments, the AMT is mounted in a customized Ford Econoline 350 van. The fixed station, located at JPL, utilizes a 2.4m antenna and a 10W high power amplifier (HPA).

Figure 1 shows the communication channels. The primary channel used for evaluation and measurements was that between Johndoe's PC and the Data Gateway via the satellite channel. The most demanding configuration was the connection from Janedoe's PC located in New Jersey, via the RAM network, via the AMT van (effectively acting as a mobile base station), over the satellite, through the Data Gateway located in Los Angeles, and back over the Internet to a user back in New Jersey.

2•3 Protocol Description

An important question related to satellite-terrestrial interoperability is whether the data communications protocols can operate efficiently across multiple channels. Most protocols in use today (e.g., TCP/IP) have been optimized for wireline channels; their use over wireless networks presents significant new challenges. The radio and free space channels characteristic of these networks introduce noise, multipath interference, shadowing, and weather effects that can cause higher bit error rates and longer periods of increased bit errors than their wireline counterparts. Host motion creates time-varying communication paths that can cause packet delay, misordering, duplication and loss. In addition, the satellite-link channel can add significantly to the round-trip packet delay, especially when geostationary satellites are used. As currently envisaged, both terrestrial and satellite systems will operate in bandwidth limited channels where efficient use of the spectrum takes on great importance.

These experiments used two independent protocols: the AMT communications protocol for the satellite link, and TPE located in the end systems.

2•3•1 AMT Communications Protocol Description

The AMT provided the satellite communications between terrestrial devices including the Data Gateway, the portable PCs, and the RAM modem. These devices interfaced with the AMT system by sending packets through a standard asynchronous RS232 serial port. However, the AMT system is based on synchronous data transmissions, with specially designated signals to control data flow. To minimize development time and costs, the discrepancies in data flow between the devices and the AMT system were handled by modifying the existing open-ended, unacknowledged, full-duplex AMT communications protocol (similar to that used for a voice link).

This modified AMT protocol maintained a link at all times (circuit connection); any data received was immediately transmitted over the satellite link with minimal buffering. In order to maintain the communications link during periods when there was no data from the device, the protocol transmitted uniquely identifiable "fill" bytes. On the receiving end, the protocol removed the fill bytes, passing only data bytes to the receiving device.

A satellite fill pattern was chosen that could not occur in the Serial Line Internet Protocol (SLIP) [3]. As SLIP uses an escape byte of 0xDB (i.e., 1101 1011), with escape-end being 0xDBDC and escape-escape being 0xDBDD, we chose the uniquely identifiable fill pattern of 0xDBDE.

2•3•2 Wireless Protocol (TPE) Description

For error control an experimental transport protocol, called **TPE**, was used that was optimized for wireless networks, The main objective was to understand the types of mechanisms and parameters desirable on wireless networks (we did not address where the error control should be located). This section gives an overview of TPE, more details can be found in [4].

TPE uses the following message framing mechanism:

- Framing into **chunks** that fit inside a network packet.
- Transport Protocol Data Units **(PDUs)** made up of an integer number of chunks.
- Signaling to reduce the chunk header size.

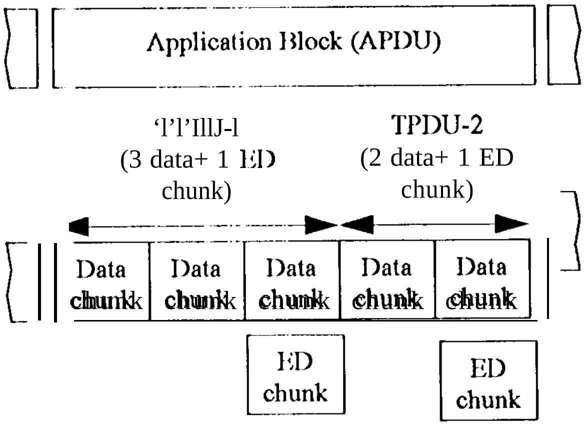

Figure 2 **Segmentation of an application block into data and error detection (ED) chunks**

Figure 2 shows an example of how TPE segments an application PDU **(APDU)** into 5 data chunks. In addition, TPE adds 2 error detection (ED) chunks, because the application block was split into 2 Transport PDUs **(TPDUs)**. TPE moves chunks directly to and from main memory - application data is never copied at the level of APDU or TPDU. in the field trials, TPE added 8 bytes/

packet for chunk header, put exactly one chunk into every packet.

The TPE's error control mechanisms operate on the TPDUs. The main mechanisms are:

- Error detection using a powerful 32-bit code.
- ARQ (Automatic Repeat reQuest) with selective acknowledgment and retransmission.
- Combining data from multiple transmissions.

TPE sends a 4 byte error detection parity per TPDU, encoded using the Weighted Sum Code. The Weighted Sum Code has similar error detection properties to the CRC, but can be calculated faster.

TPE corrects errors by retransmission. TPE uses a computationally demanding form of ARQ: using selective-acknowledgments (receiver sends a list of correctly received TPDUs) and selective retransmission (transmitter only resends those TPDUs that are unacknowledged).

TPE combines chunks from multiple partially received TPDUs to make up a complete TPDU. Thus, when a TPDU is retransmitted, the receiver only processes the missing chunks (eliminating duplicate chunks).

To allow fast set-up and robust connections, TPE uses two key mechanisms:

- Fast opening& closing of unreliable **connections.**
- Reliable **sessions.**

Using timer based connection management, connections are set-up without a three way handshake, allowing data to be sent immediately after a set-up message.

2*4 *Applications*

For these trials, four messaging applications designed to suit mobile users were developed. Figure 3 shows the relationship among the applications, the wireless networks, and the error control protocol. All the application and protocol software executes on PCs running UNIX[1]. The server applications ran on the Data Gateway, and the client applications on the two portable PCs, The applications on the portable PC's had an X-windows[2]/Motif interface. The four messaging applications were: a) E-mail, b) Fax, c) Call Command and d) Credit Card Verification.

The E-mail application allows mobile users to exchange text messages with any machine on the Internet. The Fax application sends and receives standard Group III faxes between a mobile user and any standard fax machine connected to the PSTN. Both the E-mail and Fax application servers reduce bandwidth on the wireless link by sending only a small mail/fax header automatically to the mobile use]. The user is informed of the incoming message and can decide whether to request delivery of the (potentially large) body of the message.

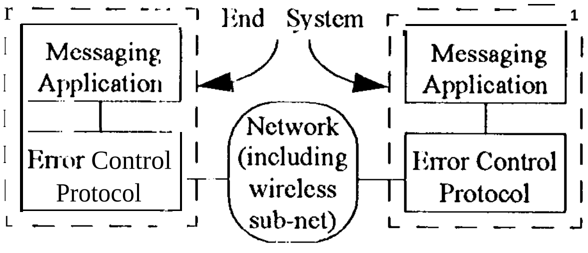

Figure 3 Logical Network Architecture

Call Command [5] is a personal telephone management application that enables users to redirect telephone calls in real time. If someone calls Janedoe, the Call Command server (the Electronic Receptionist) tells the caller to wait while Janedoe is contacted, The Call Command server sends information about the incoming call to Janedoe's portable PC. Upon receiving the notification, Janedoe can route the call directly, either to any local phone, to voice mail, or to another person,

The Credit Card Verification application was designed for field service and sales people submitting charges for equipment or services anywhere within the radio coverage area. The user scans a credit card, causing a window to pop-up (on the portable PC) with the information on the card. When the user enters the amount of the transaction, it sends a message to the credit card server. A database at the server (the Data Gateway for this case) stores valid credit card numbers and available credit line. After checking the database, the server sends a message back either authorizing or rejecting the transaction.

2•5 *Experiment Procedure*

During the Los Angeles and Morristown field trials, experiments were conducted under varying channel conditions in order to characterize hybrid satellite-terrestrial personal communications. Both stationary and mobile tests were conducted at various signal strength levels.

For the stationary tests, the bit signal-to-noise ratio $(E_b/$ NO) was varied from as low as ~5dB to as high as ~14dB. The E_b/N_0 was measured by filtering the received signal with a known noise equivalent bandwidth (BW) filter and feeding that output into a power meter. Using an initial noise power only reading plus the filter BW, and bit rate, the DAS was capable of calculating the E_b/N_0.

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[1] Unix is a registered trademark of Novell. Inc.

[2] X-Windows is a trademark of MIT.

For the mobile tests, the E_b/N_0 was set at a high level (-13dB) to allow characterization of shadowing and fading events. Tests were run in both clear weather (LA in August) and inclement weather (New Jersey in January). In addition, runs were taken on roads with clear line-of-sight (LOS) to the satellite as well as roads with foliage and/or buildings that disrupted the clear LOS to the satellite.

Each of the four messaging applications was tested under the various field conditions. These applications were used to determine the behavior of wireless messaging applications in a mobile satellite environment. In order to characterize the protocol, a simple file transfer application was used which sent a 100 kilobyte file from the portable PC to the Data Gateway and vice versa. By sending the same tile, we were able to gauge the relative signal strength at the various locations. TPE was instrumented to collect statistics at the transmitter and receiver as they affected packets and TPDUs.

Normally terrestrial radio errors are presented in terms of bit error rates; however, in this case the error control mechanisms that work at the packet and TPDU level were of greater interest. These packet and TPDU error control mechanisms are complementary to mechanisms that reduce the bit error rate. Although the results presented here are not exhaustive, they lead to some interesting initial findings about a) the characteristics of radio networks as seen from the level of packet and TPDU, and b) the performance of different ARQ mechanisms in reducing packet and TPDU retransmissions.

3 Experiment Results

This section summarizes the results obtained in the field trials. All the quantitative results presented below were obtained by sending the same 100 kilobyte file (see Section 2.5).

3.1 Characterizing the radio networks

The error distribution for the mobile runs differed substantially from the error distribution for the stationary runs. Figure 4 shows that for the mobile tests, corrupted TPDUs often needed several retransmissions, while Figure 5 shows that for the stationary tests, most corrupted TPDUs only required a single retransmission.

To investigate the error distribution further, the distribution of packet errors within a TPDU was graphed. Figure 6 and Figure 7 show results from experiments where each TPDU was composed of 5 small (24 or 32 byte) packets and statistics were collected on how many of these 5 packets were destroyed within corrupted TPDUs. Figure 6 shows that for the mobile test, most corrupted TPDUs had all 5 packets destroyed. For the stationary test, Figure 7 shows that most TPDUs lost only a one or two packets. In stationary tests with larger(128 and 256 byte) packets (not shown), most TPDUs lost only a single packet,

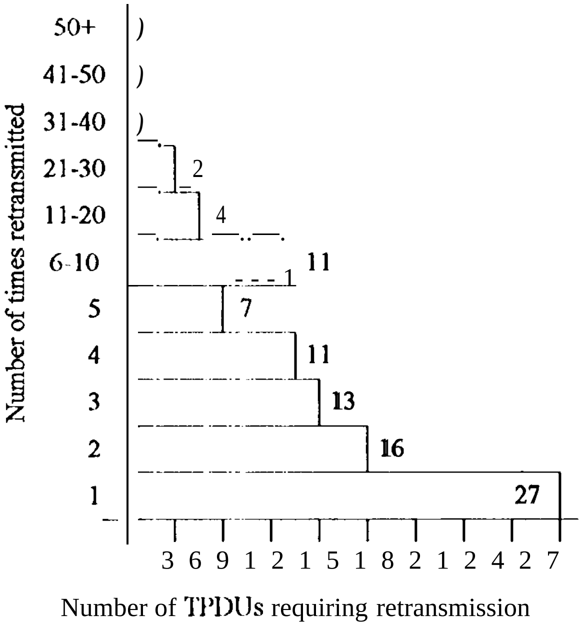

Figure 4 TPDU retransmissions for mobile tests with the satellite (~15,000 192 byte TPDUs sent)

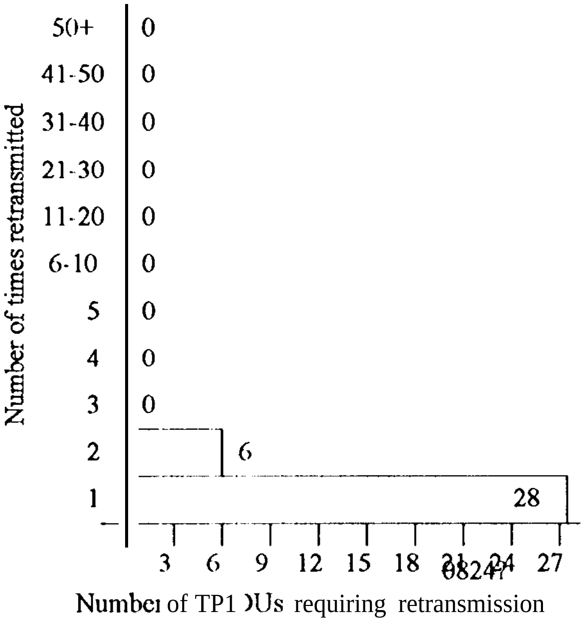

Figure 5 TPDU retransmissions for stationary tests with the satellite (~15,000 192-byte TPDUs sent)

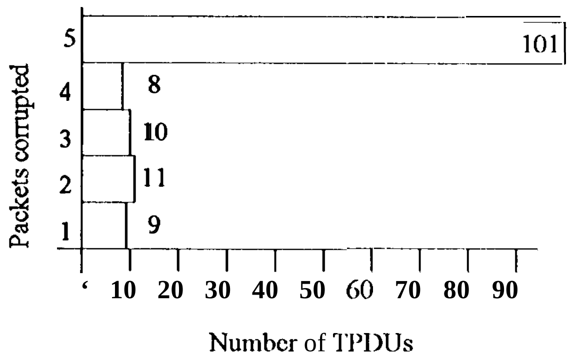

Figure 6 Distribution of packet errors within a 5-packet TPDU for Mobile Test (with ~8000 TPDUs using 24-bytes/packet)

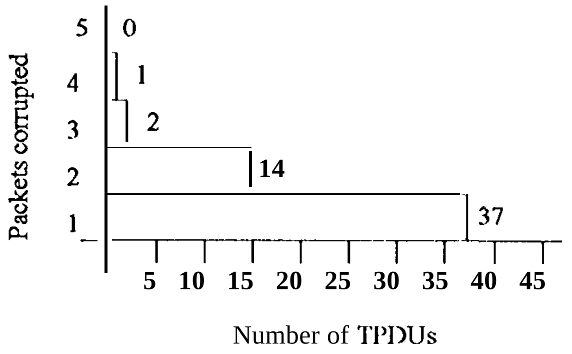

Figure 7 Distribution of packet errors within a 5-packet TPDU. Stationary Test (with -8000 TPDUs sent using 32 byte/packet)

3•2 Error Detection

The satellite-enhanced PCS trials did not utilize link error control; therefore there were many packets with bit errors. However, all errors were detected by the powerful 32-bit TPDU error detection parities.

3.3 *Packet Size*

For the satellite tests, the results on ARQ mechanisms and TPDU sizes were similar to that for terrestrial experiments conducted previously [4]. For the satellite tests we also measured the transmit time for a 100 kilobyte file with various packet sizes.

Under good conditions (with high bit signal-to-noise ratios), the use of larger packets reduced the time needed to send the 100 kilobyte file as it lessened per-packet processing overhead. For example, it took approximately half the time to send the file using 256 bytes per packet as it did using 32 bytes per packet, Under poor conditions (with lower bit signal-to-noise ratios), however, the larger packet size often took much longer than using smaller packets, and in extreme cases would result in no useful throughput.

4 Analysis

4•1 AMT system

The modified AMT protocol has several shortcomings:

- An operator is required to establish and terminate the satellite portion of the communications link,
- The satellite communications link is always maintained (circuit connection) even when no application data is being transmitted
- Frequent bit errors over the satellite link increase demands upon the end-to-end protocol.
- Corruption of the "fill" bytes into a start of frame marker caused frequent corruption of the first packet within a burst.

Although these shortcoming were acceptable for this experiment, it is evident that a more efficient protocol would be beneficial,

A new AMT communications protocol is being proposed, for use with a wider variety of asynchronous serial data devices, that eliminates the shortcomings previously described. By maintaining an appropriately sized buffer of device data, the protocol maintains communications only when device data is present, When no data is present, the satellite link is idle. The added transmission delay caused by the buffering is acceptable given the nature of most asynchronous serial data devices (messaging and data applications as opposed to voice or video).

4•2 Error Control Mechanisms

The results confirmed earlier observations on the power of power-ful error control mechanism such as selective acknowledgment and chunk combining [4].

Results obtained her-e provided new insights into the possible use of Forward Error Correction (FEC). Although no experiments were performed with FEC, the results represented in Figure 6 and Figure 7 show that a packet FEC scheme, such as that described in [6], would have worked well for stationary tests, but would have been ineffective where errors were dominated by long periods of fading, Also, results show that the number of packets of overcode should vary depending on the packet size, For example, two overcode packets per TPDU would be necessary to ensure the most TPDUs with small packets got through; while, with larger packets, a single overcode packet would have **been sufficient.**

4•3 Error Conditions and Error Control Parameters

As our results confirmed, the radio propagation **environment is** well modeled by a time-share between Rician and Rayleigh fading. Therefore, it is critical that wireless error control schemes work efficiently under both types of fading conditions. Mechanisms and parameters that work well under only one scenario will not provide robust service and will limit the range of useful operations. The results also demonstrate that dynamic algorithms are required to change the error control parameters. For example, as the bit signal-to-noise ratio decreases so should the packet size.

4•4 Applications

The four messaging applications consistently performed well in the stationary. More surprising, however, was that the applications maintained reasonable performance in the mobile tests, even when voice connections were unintelligible (messaging applications are tolerant of wide delay variation).

5 Conclusion

This paper describes results from satellite-enhanced personal communications field trials using the ACTS satellite with various wireless and wireline terrestrial networks. The interconnectivity among multiple wireless communications services shows how a mobile user can have personal services available even while outside the coverage area of a single communications provider.

The results of packet and higher layer block loss show that, even within a single wireless network, conditions vary dramatically depending on whether Rayleigh fading or Rician fading dominate the errors.

In order to deal with the varying radio conditions, we believe an efficient general wireless error control protocol requires powerful error control mechanisms and sophisticated dynamic control algorithms. With the correct block and packet sizes, a selective ARQ protocol can provide efficient error control under virtually any radio condition. Also, with the correct packet overcode parameter, an FEC scheme could provide efficient low latency error correction under some radio conditions.

Acknowledgments

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References

[1] R Wolff & D. Pinck, "Internetworking Satellite and Local Exchange Networks for Personal Communications Applications," International Mobile Satellite Conference, Pasadena, CA, June 1993.

[2] K. Dessouky & 1. Jedrey, "The ACTS Mobile Terminal," SATCOM Quarterly, JPL, Pasadena, CA, No. 8, January 1993.

[3] J. Romkey, "A Nonstandard for Transmission of IP Datagrams over Serial Lines: SLIP," Internet RFC **1055,** June 1988.

[4] A. J. McAuley, "Error Control for Messaging Applications in a Wireless Environment," INFOCOM 95, Boston, MA, April 2-6, 1995.

[5. M. Kramer, G. Ramirez, D. Turoek, R. S. Wolff, "Use of Two-Way Wireless Messaging for Personal Telephone Management," 2'nd Universal Personal Communications Conference, Ottawa, Canada, 1993.

[6] A. J. McAuley, "Reliable Broadband Communication Using a Burst Erasure Correcting Code," Proceedings of ACM SIGCOMM, pp. 287-306, September 1990.