Packet Radio in the Amateur Service

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Abstract—During the past several years there has been much activity in the development of networking hardware and software for personal computers. At the same time the amateur radio community has been equally active in the development of networking equipment and procedures especially suited for radio circuits. Although the initial efforts have been with terrestrial circuits, experimentation with and development of satellite-based systems is well underway.

While we are aware of the many commercial and government organizations active in specialized packet radio systems, our goal is to establish radio networks with inexpensive equipment that is within reach of a large number of individuals with limited budgets.

This article will provide a brief history of hardware, software, and protocol development activities as well as a description of amateur packet radio operations.

Also discussed are satellite-based operations and development efforts. These include AMSAT-OSCAR-10 and UoSAT-OSCAR-11, currently operating in orbit, and PACSAT, JAS-1, and Phase 3-C, in the design and construction phases.

I. Hardware Development

AMATEUR radio packet data communications has been done primarily with dedicated microprocessor systems called terminal node controllers (TNC's). TNC's are single board computers needing only a terminal for operator input/output and a modem to be connected to the radio transceiver. A TNC can be built from a kit or purchased assembled for $150–$500.

A TNC is typically connected to a host computer or terminal with an RS-232 DCE (data communications equipment) connector. This allows any host with asynchronous serial communications capability (e.g., a personal computer or a mainframe) to use the TNC as if it were a conventional telephone modem. The TNC handles all necessary channel protocols, and since they are often difficult to implement on personal computers which do not provide real-time multitasking operating systems, this approach allows the use of packet radio in a much wider variety of applications.

A. VADCG Terminal Node Controller

The first successful packet radio communications controller was produced by the Vancouver (Canada) Amateur Digital Communications Group (VADCG) before 1980. Amateur packet radio started much earlier in Canada because the use of digital codes other than Baudot was legalized before the same occurred in the United States. Even though amateur radio stations using the VADCG TNC are now in the minority, this project deserves mention because it was the first project of its type to gain acceptance. It provided many amateur radio enthusiasts, including the authors of this article, with their first contact with packet radio communications.

The VADCG TNC (Fig. 1) uses the Intel 8085 microprocessor. The original versions had 4K bytes of ROM for software and 4K bytes of static RAM primarily for packet buffering. HDLC frames are generated by the Intel 8273 SDLC/HDLC controller, which can be connected to either synchronous or asynchronous external modems. Either a TTL-level parallel or an RS-232 serial interface is available for connection to the local data terminal equipment (DTE).

B. TAPR Terminal Node Controller

After the legalization of digital codes by the FCC, the number of American amateurs interested in packet radio began to grow and VADCG TNC's were placed in service. Because of the desire to standardize protocols (to be discussed later) and capitalize on experience gained with the VADCG TNC, the decision was made to design and build a new TNC. In the Fall of 1981, a group of radio amateurs based in the Tucson, AZ area formed a nonprofit corporation, Tucson Amateur Packet Radio (TAPR) to design, produce, and distribute the new TNC (Fig. 2).

The TAPR TNC uses the Motorola 6809 microprocessor. To provide for more sophisticated protocols and command interfaces than can be easily accommodated on the VADCG TNC, 32K of ROM and 8K of static RAM are provided. HDLC frames are generated by the Western Digital 1933 SDLC/HDLC controller. There is also a 32 byte EEPROM (nonvolatile memory) to store installation dependent information, along with an on-board modem using Bell 202 standards.

The development of the TAPR TNC was highly formalized. One hundred and seventy-two "Beta test" units were shipped to various centers of packet radio activity throughout the United States, while "Beta test coordinators" assisted users and provided feedback to the designers. The experience gained from the Beta test proved invaluable in designing the production model. The entire design, production and distribution of the TAPR TNC was carried out with all-volunteer labor on a not-for-profit basis. Over 1000 of the latest version TAPR TNC's are now in service. Within the past year commercial versions of TNC's have

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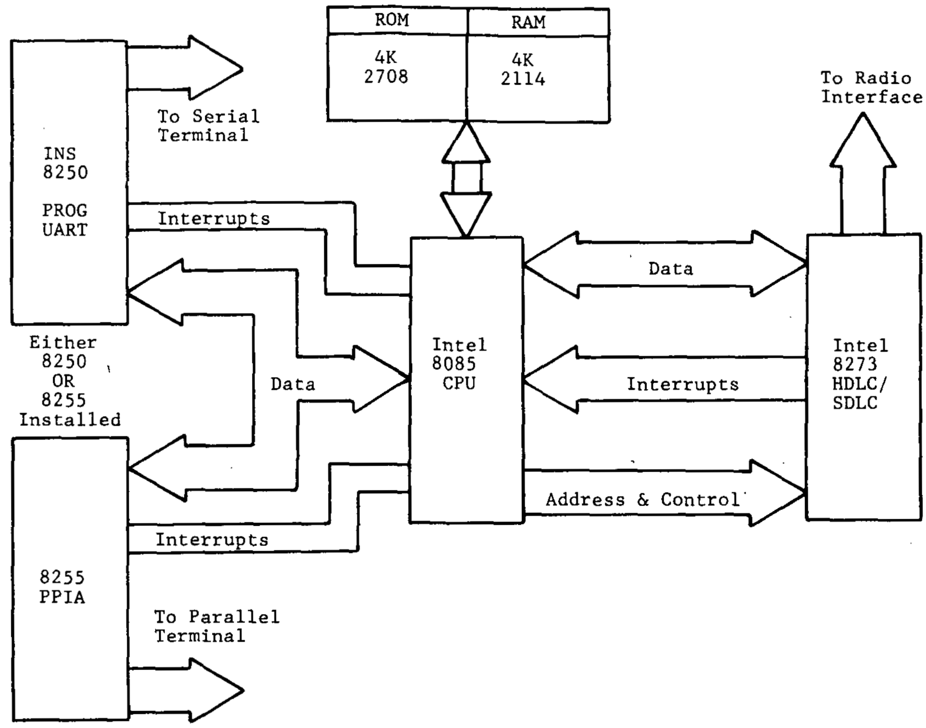

Fig. 1. VADCG terminal node controller.

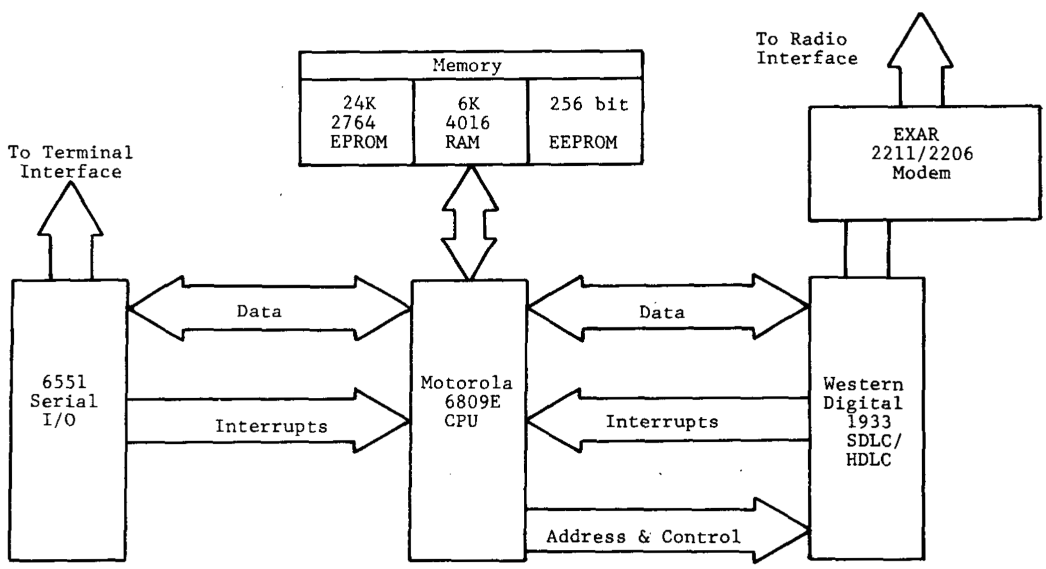

Fig. 2. TAPR terminal node controller.

been marketed and some of these are based directly on the TAPR design.

II. Software and Protocol Development

A. Background

The development of software and protocols used in amateur packet radio networks has been influenced by several factors.

1) Existing, proven commercial standards should be used whenever possible, making only those changes which are absolutely necessary to allow operation in a half-duplex shared channel radio environment.

2) The informal nature of amateur radio and particularly the low density of packet radio users initially precluded protocols requiring a central control site for address assignment or access arbitration. Evolution to more sophisticated protocols should not be precluded, but it should be possible to do so in an incremental fashion so that an enormous amount of effort is not required for each step.

B. Link Level Protocol

At the time discussions began on establishing a standard link level protocol for amateur radio, there was unanimous agreement that HDLC should be used. Experience with HDLC in the VADCG boards had shown it to be clearly superior to asynchronous transmission with respect to error detection, framing, and channel efficiency, and as these functions are built in to several commercially available HDLC controllers, this greatly simplified the TNC software.

There were, however, two schools of thought regarding the format to be transmitted within each HDLC frame. One group wanted to immediately adopt the ARPA TCP/IP and encapsulate IP datagrams directly in HDLC frames. Others felt that TCP/IP was too large a step to take at once and in any event the radio environment was unreliable enough to require a link level protocol which provided hop-by-hop acknowledgments. The alternative proposed by this group was a protocol based on the link level of X.25 which had been adapted to function on a shared radio channel.

1) X.25 In the Radio Environment: X.25 is intended to operate on a point-to-point full-duplex link, while radio is inherently a broadcast medium and is often half-duplex. While half-duplex is not a real problem (in some ways it is an advantage), the broadcast nature of radio presents an immediate difficulty to X.25, namely, the need for multiple logical links on the same channel. A meeting sponsored by AMSAT in October 1982, approved a modified form of X.25 to solve this problem. The resultant protocol, AX.25 (for "Amateur X.25") Level 2, is virtually identical to CCITT X.25 Level 2 LAPB except for the expansion of the address field to include the amateur radio call signs of both the source and destination stations, and the inclusion of the unnumbered information (UI) response frame, taken from ADCCP.

2) AX.25 Addressing: An AX.25 address consists of a call sign (6 ASCII characters maximum) plus a 4 bit "substation ID" (SSID) encoded in a seven-octet field. Each character is left-shifted by 1 bit to comply with the X.HDLC use of bit 0 in each address octet as an address extension bit. Only the last octet of the address field (i.e., the octet immediately preceding the control field) contains a "1" in bit 0; all other address octets contain zeros in bit 0. The SSID allows up to 16 distinct link addresses under each call sign. Bit 7 in an SSID octet provides the LAPB command/response frame indication formerly provided by the choice of address "A" or "B" in X.25 frames, and the other two SSID bits remain reserved for future use.

At first, we were concerned about the possibly excessive header size involved in sending complete call signs, but operational experience has proven the wisdom of this decision. The need for central assignment of special link level addresses is avoided since call signs are guaranteed to b unique worldwide by the appropriate licensing authority In addition, channel monitoring and legal station identification requirements become straightforward. This would not have been the case had link addresses been generated, as had been considered, with a hash algorithm over the call sign.

3) Digital Repeaters (Digipeaters): There is a provision for up to eight store-and-forward level 2 repeaters, known as "digipeaters," to relay transmissions when specified in optional address fields beyond the source and destination fields. Digipeaters do a function more properly done at a higher level, but until higher level procedures and software can be worked out they provide a much-needed stopgap function. In effect, a collection of digipeaters provides an unreliable datagram service with explicit routing specified by the end users, with the so-called "link level" protocol serving as an end-to-end transport protocol.

In practice, the use of one or two digipeaters in areas with light traffic work well. However, the heavy use of digipeaters in areas with much traffic leads to drastically reduced throughput and frequent link timeouts because lost or delayed packets must be retransmitted back at the source. Much effort is currently devoted to the definition of higher level protocols that will reduce the need for digipeaters.

At present, users must manually choose routes through the network based on past experience and periodically updated station listings. This scheme is similar to the ad hoc "UUCP" electronic mail network (in which systems running the Unix operating system use dialup phone lines to pass messages along a route specified by the sender of a message), and it suffers from many of the same drawbacks. The major problem is the determination of connectivity between stations not directly reachable by the user.

These and other problems await the implementation of higher level network protocols to replace the interim "digipeater" facility, and the incorporation of distributed routing protocols to allow for the automatic exchange of connectivity information. This will be an interesting challenge, as the routing protocols must handle many heterogeneous ad hoc connections over a wide performance range. In addition, given the nature of the amateur service, some links might have some rather unusual characteristics, such as asymmetries in station RF performance and part-time availability due to changing propagation conditions or satellite visibility. At the same time, the amount of storage needed to store routing tables in each node must be minimized in order to keep costs down.

4) Unnumbered Information Frame: The unnumbered information (UI) frame is present in AX.25 but not X.25. It provides an "escape hatch" for unacknowledged datagram- or broadcast-oriented functions outside the normal link mechanism. The major current use of the UI frame is for periodic "beacon" messages to announce the presence of a station on the channel and its availability for digipeater or other automatic service.

5) AX.25 Implementations: The software for the TAPR TNC described earlier is the first implementation of AX.25 and with the widespread use of the TNC the protocol has become virtually a worldwide standard. The TAPR software consists of about 3000 lines of Pascal plus another 3000 lines of 6809 Assembler. The Pascal code contains mainly the protocol itself, while the Assembler code handles I/O devices, interrupts, queueing, and other low-level functions. The software was written by persons in Tucson and Los Angeles, and regular conferences using amateur radio (voice!) helped coordinate development efforts.

Since the pioneering TAPR effort, there have been several other implementations of AX.25:

1) an 8085 Assembler version to run on the old (but still common)VADCG hardware;

2) a Z-80 Assembler version, unusual in that the HDLC controller is replaced by software to cut costs; and

3) a portable version in "C" that is forming the basis for several new TNC hardware developments.

We have found that compatibility tests between completely independent implementations of a protocol is the best way to highlight ambiguities and errors in the implementations and the protocol specification. The relative lack of such problems has also proven the wisdom of adopting an existing proven commercial standard.

C. Higher Level Protocols

Now that thousands of TNC's are in the hands of users around the world, we have returned to the issue of defining higher level protocols which will allow the interconnection of TNC's over widespread areas. While the link layer protocol from X.25 has served us well, there are many issues involved in multihop networks which X.25, as a user-to-network *interface* protocol (as opposed to an *internal* network protocol) does not address.

One of us (Karn) has proposed that IP datagrams be sent directly above AX.25 level 2, using the flow control and acknowledgment services of the latter to increase the probability that each datagram will reach the next gateway in a network path [5]. While datagram networks such as the IP internet are understood to be "unreliable," in that end-to-end transport protocols such as TCP are required to guarantee proper delivery of stream data, our experience with digipeaters indicates that link-to-link acknowledgments are still appropriate in amateur packet radio. For example, in contrast to an Ethernet, a CSMA radio network faces varying signal-to-noise ratios, interference from nodes unable to hear certain other nodes on the channel (and to defer transmissions that might collide) and the inability to detect collisions during transmission. However, the "speed/reliability" selection features provided by IP, along with the use of the UI frame in AX.25, would allow a user to specify whether or not link-to-link acknowledgments are desired.

III. Modems and Modulation

This section will describe each modulation technique either in current use of amateur packet radio or in active development, along with the areas in which each is likely to be used.

A. Audio Frequency Shift Keying (AFSK)

Most amateur packet radio currently uses a Bell 202 or equivalent modem connected to a conventional FM voice transceiver. The 202 is an old half-duplex 1200 bit/s frequency-shift-keying (FSK) modem standard that has been supplanted in telephone use by the Bell 212. However, for amateur packet radio the 202 has the powerful advantages of low cost, availability, and simplicity, as it requires no changes to existing voice transceivers. Unfortunately, it is also slow and inefficient in the use of transmitter power and channel bandwidth. However, it is likely to be widespread for some time, especially among casual and occasional packet users.

B. Direct Frequency Shift Keying (FSK)

Existing commercial narrow-band FM voice transceivers are suitable for direct FSK transmission at rates considerably higher than those supported by audio subcarriers. FSK can be generated by injecting filtered transmit data directly into an FM modulator, bypassing the audio circuitry. As many transmitters use phase reactance modulators, it is often necessary to add a variable-capacitance diode ("varicap") to the crystal oscillator, but this is a simple change.

FSK reception is also easily done by connecting a data slicer directly to the output of the discriminator. The IF filter, with a typical bandwidth of 15 kHz, does not cause appreciable intersymbol distortion until a rate of about 12 000 bits/s is reached.

As transmission speeds increase, two problems are often encountered in modems of this type. One is transmitter turn-on time; this is minimized by reducing circuit capacitor values as much as possible, and by using p-i-n diode transmit/receive switching (although this can be difficult when high transmit powers are involved). Another problem is frequency stability. Even a simple crystal oscillator (i.e., not a synthesized frequency generator) requires time to stabilize at its nominal operating frequency, and generates a "chirp" during startup. The problem cannot easily be avoided by running the oscillator continuously, since the harmonics from the oscillator will likely reach the receiver and interfere with incoming signals, unless a multiplier/divider scheme is used.

Fortunately, proper circuit design can minimize transmitter chirp, and the wide deviation necessary for high-speed transmission tends to lessen the effects of chirp and drift. Residual frequency drift and variations between stations are best handled with automatic frequency control (AFC) in the receiver, possibly combined with pseudorandom (PN) data randomizers to eliminate bit pattern sensitivities. Enough time for a synchronizing preamble at the beginning of each transmission must still be allowed for the transmitter to attain the correct power and frequency and for the receivers to set the proper slicer threshold.

As a modulation technique intermediate in complexity between AFSK and PSK (to be discussed next) direct FSK will most likely find its primary application in terrestrial "backbone" links and in advanced individual user stations.

C. Phase Shift Keying (PSK)

The use of amateur satellites for digital communications demands a modulation technique providing better energy efficiency than FSK along with the ability to track often substantial Doppler shift. The best (i.e., simplest) technique that meets these requirements is coherent binary phase shift keying (BPSK). Four hundred bits/s BPSK is already in use for the command and telemetry links of AMSAT-Oscar-10, and the modems designed for A0-10 have also been used successfully through the transponder when connected to packet radio TNC's.

BPSK modem design can be simplified when operating with HDLC. For example, one traditional problem in BPSK is phase ambiguity. Since the demodulator has an equal probability of acquiring lock such that the data stream comes out either "right side up" or inverted, the polarity insensitivity of the NRZI encoding used in HDLC eliminates the need for special demodulator hardware to correct data polarity. Also, because of the bit stuffing used to achieve transparency in HDLC, bit clock subcarriers (e.g., Manchester encoding) are unnecessary.

Because of its relative complexity, BPSK will likely find its primary use within amateur packet radio on satellite circuits. However, it is possible that the same BPSK modems designed for satellites will also be used on some terrestrial paths with marginal link budgets.

IV. Packet Network Examples

Although there is some packet radio on the high frequency (HF) bands, most has been on the very high frequency (VHF) bands and above. Because many amateur radio operators have 2 m (144–148 MHz) equipment, most activity has been on this band. Fig. 3 shows a typical packet radio operation. Two pairs of stations are in direct communication on the same radio frequency channel. Fig. 4 shows the use of a digipeater, made necessary by distance or terrain limitations.

V. Operations and Experiments

By now there are at least 2000 packet radio TNC's in service in the United States and Canada. Operations are slowly spreading to countries overseas. Activity tends to be concentrated in certain geographic areas with California, the Washington DC area, New York, New Jersey, St. Louis, and Dallas having the large concentrations of stations.

Most activity has been on the 2 m FM amateur band and the mode of operation takes different forms. Stations usually establish connections with each other on an established local frequency. Since any TAPR TNC can also act as a digipeater, stations not within radio range of each other may connect via another station. This can be done even while the station acting as a repeater is part of an established connection with yet another station. Computer bulletin boards have been connected to TNC's such that the station originating the connection can gain access to the computer to read and store messages.

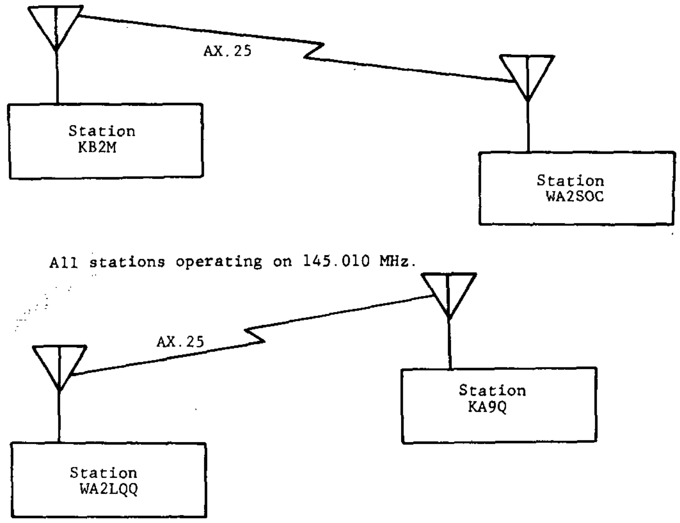

Fig. 3. Four stations in communication, two separate DCE/DTE links on the same frequency.

VI. Amateur Packet Radio Via Satellite

Perhaps the most interesting and exciting operations and experiments have been those combining packet radio with satellite communications. The combination of these two technologies will provide the greatest challenge for radio amateurs in the future.

Amateur satellites in the West are constructed by organizations affiliated with AMSAT, an international nonprofit association of amateur radio volunteers who operate largely from donations by individuals and corporations. For example, the PACSAT project to be discussed in this section has been largely supported by Volunteers in Technical Assistance (VITA), which perceives a capability in packet satellite technology to enhance greatly their goal of providing technological assistance to developing countries. Three amateur radio satellites are now in operation which are important in the development of amateur radio data communications systems.

A. *UoSAT-OSCAR-9*

The first, UoSAT-OSCAR-9, designed and built by the University of Surrey in England, does not contain a communications transponder for either voice or data but is the first amateur radio satellite to transmit spacecraft telemetry and experiment data in a computer processable code, ASCII. In addition to managing the various scientific experiments on board, the on-board 1802 COSMAC microcomputer has provided a highly successful "bulletin service" to the users of the spacecraft, previewing one of the applications for which PACSAT will be dedicated.

B. *AMSAT-Oscar-10*

AMSAT-OSCAR-10 (AO-10), launched by the European Space Agency in June 1983, is designed to operate in a highly elliptical orbit similar to that of the Russian "Molniya" communications satellites. The Molniya orbit was chosen for this satellite for two main reasons.

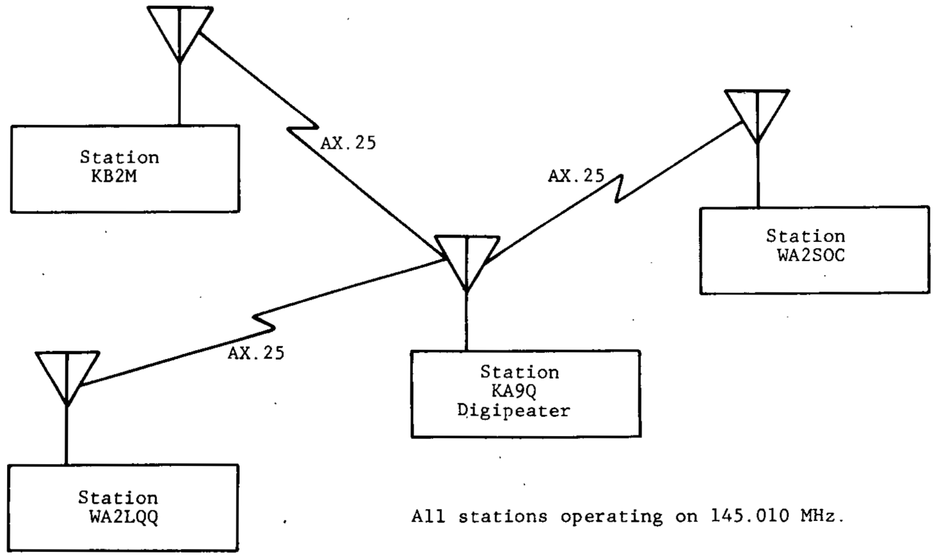

Fig. 4. Four stations, two separate DCE/DTE links with one station simultaneously acting as a repeater.

1) Spacecraft design is considerably easier (and cheaper) for the Molniya orbit than for the more conventional geostationary orbit. Although AMSAT's goals include the eventual launching of satellites into geostationary orbit, the Molniya orbit provides very similar communications opportunities (albeit not continuously) to those of a geostationary satellite.

2) Unlike a geostationary satellite, a single Molniya satellite provides part-time service to all parts of the Earth (although it may favor some areas, such as the northern hemisphere). This is an important consideration, as amateur satellites are major undertakings that require widespread international support for their realization. It would be difficult to get this support if only one region of the world's amateurs were to benefit.

AO-10 contains a linear transponder that has already been used for experimental packet work. During tests, packet radio stations on both coasts of the U.S. have been linked via satellite; one such experiment is shown in Fig. 5. The biggest current obstacle to packet radio via AO-10 is the marginal performance of FSK with the signal-to-noise ratio available. One of us (Karn) is developing a variable-speed BPSK modem which, with the improved efficiency of a coherent demodulation technique, should provide reliable transmission at 1200 bits/s.

C. *UoSAT-OSCAR-11*

The newest of amateur radio satellites carries a Digital Communications Experiment (DCE) specifically designed to test and evaluate components, software, and ground stations in preparation for PACSAT, a satellite to be dedicated to the task of store-and-forward packet switching. UoSAT-OSCAR-11 (UO-11), the successor to UoSAT-OSCAR-9, was built by the University of Surrey. It was launched in March 1984 by NASA, and after an engineering checkout period the spacecraft is fully operational.

The DCE is a greatly scaled down PACSAT. While the tasks of active attitude stabilization, transponder control, beacon management and other on-board tasks are complex, to date the demands on processor speed and memory have been small. AO-10 uses an 1802 microprocessor and 16K bytes of memory, while UO-11 housekeeping tasks are performed by an RCA CDP1802 and 48K bytes of memory. With these low speeds and small part counts, high reliability or specially prepared parts can be bought or otherwise procured. The 1802 processors are radiation hardened Sandia parts and the AO-10 memory array is shielded with a block of brass.

PACSAT, being primarily a data processing application, will far surpass the amount of processing power launched by amateurs to date. The current design calls for as much as 4 bytes of memory and up to seven microprocessors. To keep the project within very tight cost limits and our ability to provide software and other support, off the shelf parts must be used. The UO-11 DCE uses this type of technology in its design. The processor is an NSC800, a CMOS Z-80 look-alike; development tools for this chip are cheap and plentiful. Its availability in a low-power version that had been on the market for two years was the major factor in choosing the older 8 bit standard over newer 16 bit micros.

The DCE uses 128K bytes of memory, divided among four memory technologies. The memory subsystem is designed such that the banks of memory can be isolated, allowing data to be gathered as the system degrades over time. Part of the memory is designed so that single bit errors are corrected automatically by hardware, while the remainder is checked by a software routine. A hard failure of a single bit was detected shortly before launch. The DCE is programmable from the ground through a command uplink and through the 1802 main processor. Any of the three command uplinks and three telemetry downlinks can be used for message exchange.

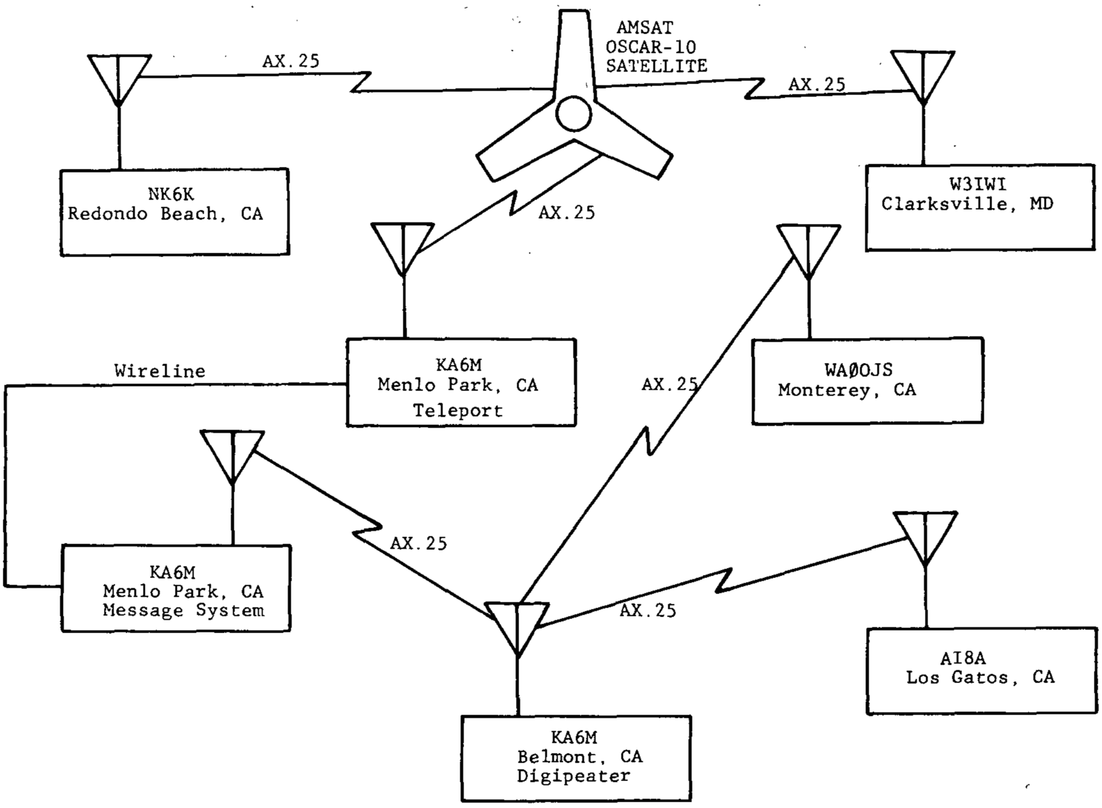

Fig. 5. A typical AX.25 linking experiment using the AMSAT-OSCAR-10 satellite. Stations WA0OJS and W3IWI established a connection. Later, stations AI8A and NK6K were connected.

The DCE also provides redundancy in the spacecraft control system. The wisdom of this design was shown earlier than expected when a failure soon after launch in a command decoder caused a spacecraft emergency. Since its recovery 10 weeks later, all commands to the spacecraft have been routed through the DCE.

D. PACSAT

PACSAT (PACket radio SATellite) will provide global digital communications with a single satellite (see Fig. 6). With a "file server" or "electronic mailbox" in low Earth orbit, PACSAT offers nonreal-time message transfer between any two points on Earth with a maximum delay of 12 hours. An Earth station, including RF and computer equipment, antennas and modems, will cost about $1000.

PACSAT is optimized for low cost and maximum coverage at the expense of real-time communication and high data transfer rates. At least two groups are ideal users of such a system: Amateur Radio operators, and an organization call VITA.

Amateur radio operators desire worldwide coverage; they are also a frugal lot. Many of the recent technical contributions by amateurs have been in communicating in ways that may already exist elsewhere, but with unconventional technologies that cost fractions of their commercial counterparts.

As previously mentioned, VITA (Volunteers in Technical Assistance), is a private nonprofit organization that provides information and assistance to people and groups in developing countries.

Their goal is to assist in the local application of economical technologies that are also culturally and environmentally acceptable. VITA has provided a free technical information service since 1959. A major problem has been the slowness and unreliability of international mail to the rural areas where the information is most needed, as question and answer exchanges can take months. While real-time audio teleconferencing experiments have been done with conventional satellites (the NASA ATS-1 and ATS-3), scheduling problems, time differences and the need for hardcopy document transmission make an electronic mail system more attractive.

As will be seen, the capabilities of PACSAT and the needs and capabilities of its users mesh nicely. For example, VITA desires an earth terminal that can be carried by one person, be battery or solar powered, and requires no knowledge of orbital mechanics to operate. Because path losses to a spacecraft in a low polar orbit on VHF/UHF frequencies are much lower than to a conventional spacecraft in geostationary orbit, a 10 W transmitter and omnidirectional antenna is suitable for a ground station. The link margins will comfortably support a 9600 bit/s data rate. This speed is about the highest that can be sustained by most of the low-cost personal computers available today.

1) PACSAT Orbital Parameters: PACSAT will operate in a polar orbit at an altitude of 600–900 km. In this orbit, the spacecraft will cover all points on the Earth at least twice each day. Only this orbit will fulfill the mission requirement of global access with a single satellite.

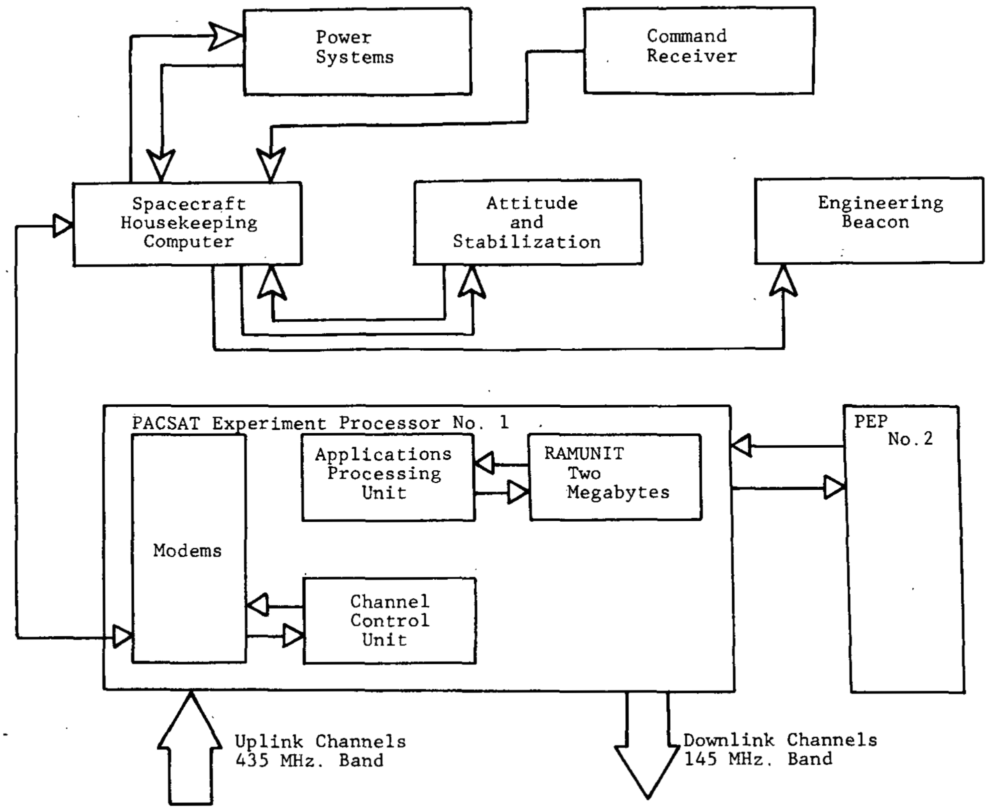

Fig. 6. PACSAT system architecture.

2) Spacecraft Bus: PACSAT is designed to be launched from a "Get Away Special" (GAS) canister by the Space Shuttle, now the primary path to low Earth orbit. The GAS program offers a low cost ($10 000) launch for payloads smaller than a cylinder 72 cm high and 50 cm in diameter and weighing less than 91 kg. Besides the mass and volume limits, the GAS imposes another problem. The Shuttle typically orbits at an altitude of 300 km; most satellites, including PACSAT, would decay from this orbit in a matter of months. Therefore, PACSAT must carry its own propulsion system.

PACSAT will use an electrothermal propulsion system where solar energy stored in a battery vaporizes a liquid as it is ejected through a small nozzle. For active attitude control, electrically powered magnetorquers will be used. Under control of an onboard navigation computer, current is applied to a set of wire coils to produce a magnetic field. This field interacts with the Earth's magnetic field, providing a rotational torque. This technique has been used successfully as the sole means of attitude control on the last three amateur spacecraft. PACSAT's solar arrays will provide about 30 W of power.

3) RF Systems: PACSAT will transmit to Earth using a 2 W transmitter in the 144 MHz Amateur Satellite allocation. This amount of power will support signaling at 9600 bits/s using binary phase shift keying, occupying about 20 kHz of bandwidth.

PACSAT will carry several uplink channels, each with the same signaling speed and modulation format as the downlink transmitter. As there will be several stations at any one time attempting to access PACSAT, greater uplink than downlink capacity allows for access contention. Since the RF systems operate in full duplex, the use of a separated band (the 435 MHz Amateur Satellite allocation) for the uplinks greatly simplifies the design of both the satellite and the ground stations. However, one unresolved concern is the potential for interference from land-based military radars with which the band is shared, as some radar pulse durations may be long enough to corrupt transmissions at 9600 bits/s.

4) Electronic Mail System: PACSAT's electronic mail/file server system will use commercially available components, although with the extremely low power available, only CMOS technology parts may be used. Several redundant modules are present, each with an NSC-800 microprocessor and up to one million bytes of RAM. A total memory complement of 4 Mbytes is planned.

Because semiconductor memories are subject to errors caused by high-energy particles trapped in the Earth's magnetic field, error detection and correction (EDAC) codes are used. The bulk RAM for message storage will use a software EDAC implementation, while local computer memories will combine Hamming read-error correction in hardware with periodic software "rewrites" to restore corrupted locations in memory before they become uncorrectable. The latter approach is working well on the three amateur spacecraft flown with onboard computers, and the soft error rates have all been well within the complete correction capability of the hardware and software.

5) Ground stations: The PACSAT ground station will interface to any personal, desktop, or mainframe computer possessing a serial data interface. The Earth terminal consists of an omnidirectional antenna, a 145 MHz receiver, a 435 MHz 10 W transmitter, a link controller (TNC), and a modem.

Link calculations for the amount of spacecraft downlink RF power available (about 2 W) show that uncoded speeds of 9600 bits/s should be readily attainable even with simple receivers and omnidirectional antennas. Most of the ground station hardware, with the exception of the modem, is already available off-the-shelf, keeping development and per-station costs to a minimum. The PACSAT modem which is under development will use binary PSK and connect to the IF strips of stock amateur transceivers. No error coding was initially planned, although we are considering it as an option to resist interference from the military radars which share the 435 MHz Amateur Satellite allocation planned for the uplink.

The remainder of the PACSAT ground station will be very similar to a terrestrial amateur packet radio station, except that a message transfer protocol unique to the part-time availability of PACSAT must be added to the TNC or implemented in the attached personal computer. Disk storage may be required to "spool" incoming and outgoing messages.

E. JAS-1

JAS-1 (for Japanese Amateur Satellite number 1) is a wholly Japanese project that will carry both a conventional analog transponder and a digital store-and-forward unit with functions similar to that of PACSAT. While the digital part of JAS-1 has much the same philosophy of PACSAT (including the use of AX.25 as the link level protocol), there are several variations which were dictated by somewhat different mission requirements:

1) A shorter design cycle, the result of an earlier launch (on the new Japanese H-1 launcher) and the use of a commercial contractor (NEC) to build the flight spacecraft.

2) The use of inverted uplink and downlink frequencies as compared with PACSAT, avoiding interference problems on the heavily populated 144 MHz amateur band in Japan, the country with by far the largest concentration of licensed amateurs in the world.

3) The use of 1200 bit/s AFSK (similar to current terrestrial packet operations) to allow the use of an unmodified FM voice transmitter on the uplink. However, the JAS-1 downlink will still use PSK, as the link budget does not permit any less efficient modes. The downlink rate will be limited to 1200 bits/s so that existing an SSB receiver can be used with an external PSK demodulator operating at audio frequencies. This technique has worked well with the 400 bit/s telemetry link on AMSAT-OSCAR-10.

The orbit of JAS-1 will be at an altitude of approximately 1500 km with an inclination of 50°. Unlike PACSAT, this will not be "sun synchronous"; i.e., passes over a given location will not always occur at about the same local time. However, the higher altitude will result in longer duration passes, somewhat compensating for the use of slower transmission rates.

F. Phase 3-C

Initial studies are underway to consider the inclusion of a PACSAT-like packet radio payload aboard the Phase 3-C spacecraft scheduled for launch in 1986 aboard an Ariane IV launcher. Phase 3-C will succeed AMSAT-OSCAR-10 (known as Phase 3-B before launch) as a high altitude real-time communications satellite. The design of this unit is currently preliminary, but it appears that enough power will be available to run a data rate of 2400 bits/s, using binary PSK.

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