Modulation and Access Techniques for PACSAT

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ABSTRACT

This paper describes work underway within AMSAT to define modulation, channel access methods, and related system-level considerations in the design of the store-and-forward packet radio satellite known as PACSAT.

This is not intended as a comprehensive design specification, primarily because one doesn't yet exist! In particular, only those decisions primarily concerning spacecraft hardware design are emphasized here, since the details of control algorithms, protocols, etc, will reside in software capable of being changed and reloaded into the onboard computer(s) after launch.

1. Orbital Considerations

PACSAT is intended to operate in a low altitude, polar orbit with the special characteristic that the satellite is accessible from any point on earth at least twice every day, at about the same local time each day. These so-called "sun synchronous" orbits are frequently used by weather and earth resources missions. Oscars 6, 7, 8 and 9 are all in sun synchronous orbits, so many amateurs are already familiar with them.

The low altitude and relatively high velocity of such a satellite has several implications for communications:

1. For most earth locations, a sequence of two or three passes occurs twice daily, as the turning earth carries the station through the orbital plane every twelve hours.

2. Coverage at any given time is relatively small and continuously changing. A geostationary satellite "sees" a fixed portion (41%) of the earth's surface. By comparison, Oscar-8 covers all points on earth at least twice per day, but when it is directly over the north central US, it can only see North America.

3. Passes are short. A typical pass may last for only 15 minutes from horizon to horizon. For digital communications, the highest possible bit rate is desirable to maximize the amount of communication that can be carried during a pass, although for operational flexibility the spacecraft downlink transmission rate will be under the control of a command station.

4. Path losses are modest, approximately 25-30 dB lower than to geostationary satellites. This may allow the use of lower transmitter power, omnidirectional antennas, or less efficient modulation techniques, all of which help reduce costs.

5. Doppler shift is significant. At 70 cm, horizon-to-horizon Doppler shift can be as much as plus or minus 10 khz, requiring some form of automatic frequency tracking for optimum performance. Extra wide receiver filters and noncoherent demodulation will tolerate Doppler shift, but at the cost of reduced performance.

6. Propagation time is short, ranging from 3 milliseconds when the satellite is overhead to 12 milliseconds on the horizon. Therefore, a communication protocol requiring close interaction between the satellite and its users would not unduly penalize performance except for very small packets.

2. Downlink Margins

In designing a communications spacecraft, there are always practical limitations on power, size and weight, often with the emphasis on power. Hence, the power available for the spacecraft transmitter becomes the limiting factor in the overall system design. For this reason, it is helpful to start our analysis with a stated, realistic value. This immediately provides insight into the range of modulation and bit rate options available, therefore, AMSAT's best estimate of RF output power for PACSAT is P-2 watts.

For a spacecraft in an Oscar-8 orbit (altitude 900 km), path loss on two meters would vary from 135 dB when the satellite is directly overhead to 147 dB with the satellite on the horizon, a range of 12 dB. Since even during an overhead pass the satellite spends most of its time "nearer" the horizon than directly overhead, we will be conservative and use the horizon figure in subsequent calculations.

Given that approximately 1 watt of transmitter output power is available on 2 meters, and that omnidirectional antennas are used both on the spacecraft and on the ground, receiver- input power would be -147 dBW (-117 dBm, or .3 microvolts into 50 ohms.) A receiver with a bandwidth of 15 khz and a noise temperature of 300 K would generate an equivalent. input noise power of -162 dBW, for a carrier-to-noise ratio of 15 dB, adequate for a low bit error rate with virtually any digital modulation scheme. However, since the satellite will move rapidly, use a real antenna with unavoidable pattern nulls, and often pass behind such real-world obstructions as trees and hills, additional margin is desirable.

This could be achieved in several ways, by

1. Reducing the receiver bandwidth. Each factor of two reduction would improve the carrier-to-noise ratio figure by 3 dB. However, for a given type of modulation, this reduces the bit rate, which is undesirable because it limits the amount of traffic that can be sent during the relatively brief passes.

2. Using more sensitive receivers. It is now quite easy to find inexpensive preamplifiers with low noise figures. However, external noise then becomes a factor, limiting the degree of improvement possible.

3. Using gain antennas with automatic tracking. Techniques for this have been experimented with by AMSAT members for several years, and soon will be within the realm of the average user of the Phase-3B spacecraft .

   Although the computation of antenna pointing angles has become very easy (the AMSAT ZX 81 project uses that very inexpensive personal computer for the task), the gain antennas are still relatively large and require fixed locations. We should therefore require gain antennas only as a last resort, in the sense that it should be possible to make effective use of PACSAT without them.

4. Using more efficient modulation methods. There exist techniques which can give much better performance in the presence 0f noise which are not yet widely used in the Amateur service. Many of these techniques have been widely used in commercial terrestrial and satellite services, but until now, they have often been considered out of reach of the average amateur because of cost and complexity, However, advances in digital electronics has de-coupled the issue of cost from complexity, bringing these techniques within reach of the average amateur.

3. Modulation Alternatives

We feel that the modulation method chosen is a crucial element of the PACSAT design, and I will spend the next part of this paper evaluating our alternatives.

3.1 AFSK-FM

Audio frequency frequency--shift-keying on an FM carrier is the technique currently in widespread use f0r terrestrial amateur packet radio, with the Bell 202 modem frequencies (1200 and 2200 hz) a de-facto standard. In the amateur- satellite service, UOSAT-Oscar-9 uses bit-coherent AFSK-FM for its VHF and UHF telemetry, with tone frequencies of 1200 and 2400 Hz - close enough to those of the Bell 202 to allow the use of that (non-coherent and therefore non- optimum) modem by the maj0rity of stations receiving telemetry.

AFSK- FM has several major advantages: it is cheap, simple, and allows the use of general-purpose transceivers without modification. Doppler tracking Is relatively easy, since most amateur FM receivers have sufficient bandwidth to allow large frequency deviations (e.g, 1 khz) without significant degradation of bit error rate, and the modulation tone frequencies are not directly affected by Doppler shift.

Despite its simplicity, however, AFSK-FM has serious disadvantages for satellite use, which rule out its use in PACSAT:

1. Inefficient bandwidth utilization. A 15 khz channel is used by UOSAT to carry a (maximum) 1200 bps data stream, a bandwidth density of only .08 bits/hertz. Particularly

in the 2 meter band, spectrum efficiency is an important consideration.

2. Poor noise performance. Since AFSK-FM is essentially doubly-modulated FM, it exhibits a very sharp noise threshold at a relatively high carrier-to-noise ratio, and suffers greatly from impulse noise. Subjective experience with reception of the 350 milliwatt 145,825 MHz UOSAT-Oscar-9 telemetry beacon shows that pulse noise, e.g., from power lines, causes significant errors even at signal strengths otherwise sufficient to cause "full quieting" in the baseband FM channel. Local impulse noise and fades below threshold due to spacecraft rotation and polarization losses cause many errors, despite a theoretically good link margin.

3.2 FSK

Although in common use on the HF amateur bands, "straight" frequency shift keying (FSK or F1) has not yet come into widespread use on the higher frequency bands. FSK at VHF can be implemented with simple modifications to most conventional VHF-FM transceivers; a direct input to the modulator and a slicer on the discriminator output is required. The spectral efficiency of FSK can be as high as 1 bit/Hz; for our working bandwidth of 15 khz, FSK could realistically support a data rate of at least 10 kbps.

The Bell System's Advanced Mobile Phone Service (AMPS:, uses NBFM voice transceivers with 8 khz peak deviation, 30 khz IF bandwidth, and discriminator detection to carry a biphase-encoded 10 kbps FSK signaling channel. In bipkase encoding, the data stream is exclusive-ored with a clock at the bit rate, resulting in a signal with no DC component whose energy is concentrated about a frequency equal to the bit rate.

This allows an "indirect FM" (phase modulated) transmitter to be used, provided an integrator is inserted between the bi-phase encoder and the modulator. This is a direct adaptation of FM techniques used to encode data on disks and high-density magtapes. Since in FM the baseband (demodulator output) noise level increases with increasing frequency, a practical limit to the bit rate exists requiring relatively high receiver input C/N ratios when operating at high rates. In AMPS, considerable retransmission redundancy is also provided since multipath fading, not gaussian noise, is the primary source of errors in mobile radio.

AMPS is evidence that high rate FSK is practical given a sufficient C/N ratio. Performance would be better with PACSAT, since multipath fading is less severe in satellite channels than in terrestrial mobile radio, except when the satellite is near the horizon. For our working C/N figure of 15 dB, noncoherent reception of FSK (e.g., with an ordinary FM discriminator) would provide a theoretical bit error rate of about 10^-7; acceptable, but with little margin for implementation losses and fading. For example, if C/N dropped to 12 dB, the bit error rate would jump to 5 x 10^-4.

Because of the tight C/N margin, Doppler correction is required in order to allow narrow receiver bandwidths no wider than the signal. Since biphase encoding produces no baseband DC component, Doppler could be tracked by a simple integrator connected to the discriminator output.

We can rule out use of noncoherent FSK modulators for PACSAT, because it will be shown later that another modulation technique (MSK) exists which is compatible with simple FSK demodulation but also allows coherent detection with a 3.5 - 4 dB improvement in bit error rate. However, our analysis of noncoherent FSK is useful because it indicates the performance that could be expected if MSK is demodulated with an FM receiver.

3.3 DSPK

Differential Phase-Shift Keying (DPSK) is relatively new to amateur radio, but will be used by AMSAT for the Phase III spacecraft engineering beacon. DPSK has significant advantages: it is fairly bandwidth efficient, works very well in low carrier-to-noise levels, and can automatically track Doppler shift if correctly designed.

DPSK is actually a modified form of true PSK in that the change (or- lack thereof) in carrier phase between each bit interval is used to determine the output state. In true PSK, the absolute phase of the carrier during each bit interval determines the output state, which requires an absolute phase reference at the receiver. If a clock is derived from the incoming data stream, there would be a 50-50 chance that the receiver would synchronize 180 degrees from the correct value, resulting in a 100% bit error rate! Differential PSK avoids this problem at the cost of having channel errors "propagate" through successive bits. However, in a packet environment where only a single bit error is needed to cause rejection of a packet and retransmission, extra errors "caused" by the first are of no consequence.

The noise performance of DPSK is considerably better than conventional FSK; for our 15 dB reference C/N, the bit error rate would decrease to 10^-10. However, the real advantage would be under marginal conditions: the bit error rate would not increase to 5 x 10^-4 until the C/N ratio had decreased to about 9 dB. Within a 15 kHz bandwidth DPSK could carry 15 kbps, although its noise performance would be degraded by such tight filtering; 9600 bps would be more realistic.

AMSAT has considerable experience with DPSK modulators and demodulators designed for 400 bps telemetry reception from Phase 3-B. Experiments have shown that non-linear transmitters are OK, and that 2.4 khz SSB transceivers are fine as long as compensation is made for the nonlinear phase response characteristic of SSB IF crystal filters.

The Phase 3 telemetry decoders use Costas loop carrier recovery which provides optimal performance, but may take an excessively long time to lock up in a multi-access packet environment. However, very simple DPSK demodulators exist that require no clock recovery circuit and are able to lock up in essentially a single bit time. These methods work at the expense of noise performance; the figures quoted above refer to this form of demodulation, while the Phase 3 demodulators do somewhat better.

NASA has also made extensive use of low cost, low-speed, (100-400 bps) doppler-tracking PSK systems with low altitude satellites for applications including remote data collection and search-and-rescue.

3.4 MSK

Minimum Shift Keying (MSK) is a hybrid of FSK and PSK. It can be regarded either as coherent FSK with a shift of exactly one-half of the data bit rate, or as PSK where the modulating waveform is a triangular ramp produced by integrating the binary input signal. Another equivalent way to look at MSK is as quadrature PSK (PSK with four possible phases instead of two) in which the quadrature channel carries the same data as the main channel but delayed by one-half bit period. In fact, the usual method for optimally decoding MSK involves building two PSK demodulators with combining circuitry; clearly this is more involved than a simple PSK demodulator.

One of MSK's advantages over PSK is that is requires minimal filtering to reduce its bandwidth to the minimum required. It has a constant envelope amplitude, unlike bandwidth limited PSK, allowing it to pass through a real-world linear spacecraft transponder with minimal intermodulation distortion to other signals, It can also be passed through a nonlinear (e.g., Class C) amplifier without the envelope distortion and resultant bandwidth-spreading that occurs with DPSK signals. The other advantage of MSK, perhaps the major one for our application, is that it can be decoded with simple noncoherent FM discriminators with a theoretical 3.6 dB loss of noise performance.

Optimally decoded MSK and PSK have almost the same performance in the presence of Gaussian noise. However, MSK has a significant advantage over PSK in cases of adjacent channel interference, due to MSK's smaller bandwidth. Tighter IF filters can be used with less performance degradation, and it should be easier to attain a rate of 15 kbps in our 15 khz bandwidth. Differential decoders eliminating the need for carrier recovery, similar to those mentioned earlier for DPSK, exist for MSK but are not as simple.

3.5 Discussion: MSK vs. DPSK

The "votes" are not yet all in among the PACSAT system definition and design team, although we have narrowed the choice to one between DPSK and MSK. MSK's most significant advantage is clearly its compatibility with simple noncoherent demodulators such as an FM discriminator,, However, this penalizes those who want to "do it right", as optimal demodulation of MSK essentially requires building a PSK demodulator twice.

We could go with a form of DPSK essentially similar to that used by the Engineering Beacon on the Phase 3 spacecraft, except at a higher bit rate. While there is strong interest in MSK for AMICON (Phase 3) data communications, the relatively short time available to settle major hardware-related PACSAT issues could cause us to choose the simpler technology, i.e., DPSK. While the FSK demodulator compatibility feature is no doubt attractive, optimal demodulators for PACSAT would be produced by AMSAT on a relatively large scale, and would probably be a small fraction ($50 - $100) of the total station cost.

Either method would provide means for Doppler correction. The Phase-3B telemetry receivers use Costas loop demodulators for the DPSK signal, generating as a byproduct a correction voltage indicating the offset of the downlink carrier. This correction voltage can be taken out of the receiver and applied with the appropriate amount of gain to the transmitter, tuning its frequency to compensate for uplink Doppler. While the uplink channel demodulators will probably be able to track out the frequency shift without correction, we feel that minimizing channel lockup time is important enough that correction should be provided.

4. Access Conflict Resolution

PACSAT will be a multi-access satellite, intended to serve a number of users simultaneously attempting to send messages to the satellite. The downlink transmitter will be connected to the onboard computer, not directly to the uplink receiver as in conventional "bent-pipe" satellite transponders. Despite the short propagation delay, users will not be able to monitor the immediate status of an uplink channel by listening to the downlink, as it may be busy sending down a message intended for another user. Therefore, provisions must be made to resolve uplink access conflicts. (Naturally, since only one transmitter, the satellite, transmits on the downlink, access resolution is relevant only for the uplink.)

Assume for the moment that the satellite traffic will be "balanced", that is, the amount of traffic successfully received at the satellite will be approximately equal to the amount of traffic sent back to the ground when averaged over a sufficiently long period of time. It is agreed that this is an unlikely situation, which would only be true if PACSAT were to be used exclusively for point-to-point communications. Repeated transmission of the same information from the satellite (e.g., broadcast bulletins or spacecraft telemetry) would disproportionately increase downlink loading. However, it is my assertion that a balanced traffic assumption is a useful one, as it represents a "worst case" for system design.

All known methods which resolve contention between multiple uplink transmitters require overhead, and hence more bandwidth, than downlink transmissions for which there is only a single transmitter. We are therefore tentatively planning to use the 70 cm band, which has a 3-Megahertz Amateur Satellite Service allocation (435-438 MHz), for uplink transmissions to PACSAT and the smaller 2 meter band segment for the downlink.

In the following sections, I will describe two possible access methods for PACSAT, and compare their relative merits.

4.1 Pure Aloha With Multiple Uplink Channels

The Aloha method calls for each station to transmit at will, without concern to interference with other transmitters. (Since stations communicating with a satellite are usually far enough apart to prevent them from hearing each other, not much is gained by listening on the uplink frequency.) The well-known maximum theoretical throughput of an Aloha channel, above which delay time rises without bound, is 18%.

A very simple and attractive scheme therefore appears. If it is desired to balance uplink and downlink capacity, six uplink channels (6 x 18% = 108%) could be provided. Each one is "equal" to the others and scanned rapidly enough by the spacecraft's onboard computer to allow simultaneous reception, at least for a time, on all six. A user station would select one of the six uplink channels essentially at random whenever it has traffic for the satellite. Since the channels are all equivalent, all that matters is that the stations distribute their traffic across the channels in order to level out loading. This could be accomplished simply by allowing each station to choose an uplink frequency at random, changing it as often as desired, perhaps with each transmission. It can be shown that with a sufficient number of stations, traffic will tend to become evenly distributed over the channels.

It should be pointed out that to provide flow control, a requirement independent of the access method chosen, the spacecraft and ground computers will follow a synchronized "handshaking" protocol once a traffic transfer starts. If the ground computers are "patient" enough, that is, they allow enough time for processing and queuing delays aboard the satellite, collisions would result only when new stations initially access the satellite.

In addition to providing flow control, the go-ahead messages to each station could include a "recommended" uplink channel to use. Based on channel loading statistics kept in the spacecraft computer, the ground station would still be free to use any channel it wished, although following the recommendation would improve uplink traffic distribution.

4.2 Reservation Aloha

The "anarchy" of the Aloha system could be reduced somewhat, with an associated improvement in spectrum efficiency, at the cost of extra discipline in the ground station computers and added delay.

One of the uplink channels is designated as the "calling channel", on which stations transmit their initial requests for service to the satellite. This is in contrast to the last scheme, in which a new station may request service at any time on any channel. Requests would indicate the amount of service desired, and because they would be short, traffic on the calling channel would hopefully be well below the 18% "total bedlam" figure. The satellite responds by granting the requesting station permission to transmit its traffic on a specific frequency during a given time "slot". Depending on the length of the time slots and the tightness of their scheduling, each station might to compute and compensate for propagation delays which change continuously during a pass.

There are two advantages of Reservation Aloha:

1. New stations requesting service would not interfere with data exchanges already in progress on the working channels.

2. Due to the tight scheduling of the working channels, fewer of them might be necessary, reducing spacecraft hardware complexity.

4.3 Discussion: Pure Aloha vs. Reservation

These two schemes represent specific points in what is actually a fairly continuous spectrum of alternatives between "total anarchy" and "total discipline". The "more disciplined" reservation scheme with the designated calling channel can potentially provide better channel utilization than the pure Aloha method; however, it suffers from an "Achilles Heel" in that it is much more susceptible to jamming, accidental or otherwise, particularly on the calling channel. With any channel usable both for calling and working, the multi-channel Aloha system provides built-in redundancy against certain hardware failures as well as jamming. For this reason, along with the strongly attractive feature of simplicity, we feel that each channel should be equivalent, although by ground software convention one channel could be used primarily for initial service requests.

While the throughput of Aloha may seem low, the 18% figure is valid only for a very large number of users; "excess capacity" exists in systems with a small number of users, especially those in which one user presents most of the traffic load. If it turns out that uplink loading becomes a limiting factor (unlikely for reasons discussed earlier), it would be possible to change operations to a "slotted Aloha" access method. This would involve programming the ground station computers to "agree" that a reference event, e.g, the beginning of a certain telemetry frame periodically interspersed into the downlink data stream, represents the beginning of a packet slot. If the ground stations were to time their transmissions to coincide with such slots, the utilization of each channel could double to 37%, and this improvement could be obtained with no changes to spacecraft hardware or software. However, each station would have to compute and correct for the varying propagation delays to the satellite as in the Reservation Aloha system.

5. Summary

This paper has presented and discussed the various modulation and access method alternatives available to the PACSAT design team. It must be emphasized that the conclusions reached here are preliminary; only after considerable simulation, experimentation, and breadboarding activity will the final decisions be made.

In any case, it is probably true that we have already "over-engineered" the PACSAT uplink in that the downlink will almost certainly become the throughput-limiting factor. Now if we only had a few more watts of power....

6. Credits

The ideas presented here actually represent those of a large number of AMSAT people in addition to the author, including but not limited to:

- Dr. Thomas A. Clark, W3IWI, AMSAT USA President and perhaps the initial "instigator" of the PACSAT concept;

- Mr. Den Connors, KD2S/7, Assistant Vice President for Engineering, Spacecraft Systems and PACSAT Project Manager;

- Dr. John L. DuBois, W1HDX, Phase 3 Ground Command Station Coordinator;

- Mr. Jan A. King, W3GEY, Vice President for Engineering;

- Dr. Karl Meinzer, DJ4ZC, President AMSAT-DL;

- Dr. Stephen E. Robinson, W2FPY, Assistant Vice President for Engineering R&D

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