FSK Methods for PACSAT Communication

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ABSTRACT

The authors propose that PACSAT employ several 9600-bit/s noncoherent FSK uplinks and a 9600-bit/s coherent FFSK downlink. This combination of modulation schemes provides for simple groundstation transmitters, groundstation demodulators of several classes of complexity, and staged development of space-rated systems. A research plan is identified which will result in simple spacecraft systems being available quickly and optimised spacecraft systems being developed as time permits. Areas for further study, resulting in 1.5:1 increase in bit rate with no increase in signalling bandwidth, are discussed.

1.0 MISSION PROFILE

Amateur packet radio has expanded greatly in the three years since Den Connors paper "The PACSAT Project" appeared in the 1983 Proceedings [1]. The need for a reliable, high-throughput, world-wide packet service is much greater now than it was 3 years ago; 300-bit/s HF stations cannot continue to provide acceptable long-distance service to exponentially-expanding VHF metropolitan networks. The general objectives and parameters of the PACSAT mission have changed little since the project was first discussed: PACSAT will be a store-and-forward mailbox placed in a polar, low-earth orbit. The mailbox will be served by several 9600-bit/s uplink channels and a single 9600-bit/s downlink. PACSAT will use the AX.25 link-layer protocol, making it compatible with an installed base of more than 10,000 TNCs. Delays in the PACSAT project, caused by lack of funding for the mission, have had some positive results: the volume and power consumption of large RAM devices have decreased, whilst the availability of such devices has increased; current plans call for PACSAT to carry at least 4 Mbytes of message-storage RAM,.

It takes a firm launch opportunity and commitment of funding to solidify the design of any satellite, and in the absence of these stabilizing influences, PACSAT has gone through many design meetings and design revisions. Time has not been wasted, however; experience gained through design, construction and operation of the UoSAT-2 DCE [2] has taught us much that will be of direct use when we begin to work in earnest on a dedicated PACSAT spacecraft. During this time, the UoSAT group at the University of Surrey (UoS) -in the UK has become very interested in store-and-forward communications using satellites in low earth orbit. Our interest has moved past the role of supplying a spacecraft "bus" for the PACSAT mission toward actually taking part in the design and construction of the payload. Whatever for-n UoSAT-C takes (and there are several possibilities now being investigated') it will probably carry a PACSAT-like transponder, With this in mind, the authors (with the help of many others both within and outside of UoS) have carried out an investigation of two critical PACSAT design issues: modulation and demodulation, These topics have been discussed by Phil Karn [3], but we feel it enough significant developments have taken place to warrant further investigation,

2.0 LINK BUDGETS

The following discussion is driven by the satellite link budget, as calculated by M. Awan (UoS). This budget assumes that the satellite is to be small and inexpensive, thus dictating a low-power downlink transmitter. The orbital altitude assumed for these calculations is 900 km.

2-Meter Downlink Budge':

Transmitter power	4 W)	36 dBm
Transmit losses		- 2 dB
Antenna gain		0 dBi
EIRP		t34 dBm
Free-space path loss at 145 MHz		-146.3 dB
Carrier power received by groundstation (isotropic antenna)		-112.3 dBm
Noise density for receiver (1 dB noise figure. 300 K equivalent antenna noise temperature.)		-172.9 dBm/Hz

Carrier-power to noise density ratio (l-degree satellite elevation, isotropic antenna.)	60.6 dB/Hz
Bit rate (9600 bit/s)	39.8 dBHz

Available energy per bit divided by the noise-spectral density (Eb/No).	20.8 dB

Rather than assume a perfect system in which this high signal-to-noise ratio is available to a demodulator, Mr. Awan has included an implementation margin in his calculations.

Modem loss	2	dB
Antenna pointing loss	1	dB
Antenna ageing	'	dB
Desense due to transmitter	1	dB
Man-made interference	3	dB
Polarisation mismatch	3	dB
Multipath cancellation	1	dB
System Margin	2	dB

	14.0	dB

Subtracting this from the previous result	20.8 dB
	-14.0 dB

Available Eb/No with satellite at 1 degree elevation, with OdBi-gain receiving antenna.	6.8 dB

Assume that our demodulators need 15 dB Eb/No to produce a bit error rate (BER) of 1E-6 (as discussed below).

Eb/No at demodulator	15 dB
Eb/No available with 0-dBi gain antenna with satellite at the horizon.	- 6.8 dB

Necessary antenna gain.	8.2 dBi

Thus, an 8.2 dBi gain receiving antenna is necessary for 9600-bit/s, 1E-6 BER communication when the satellite is at the horizon. A station so equipped will have excess antenna gain when the satellite is high in the sky, and stations with less gain will have coverage for less than the full horizon-to-horizon satellite pass. Table 1 shows the antenna gain required at elevations from horizon to 90 degrees, as calculated using the above assumptions.

2.1 Possible Downlink on 70-cm?

The above link calculations assume a 2-meter downlink PACSAT could, however, downlink on 70-cm (435 MHz). The difference in free-space path loss between 2-m and 70-cm is about 9.5 dB. Since we must keep the satellite small, this 9.5 dB cannot be made up by simply increasing downlink power or providing antenna gain on the spacecraft. Groundstations would have to increase their antenna gain, but antennas the same size as required for two-meter downlink reception would produce about 3 dB more gain on 70 cm. Additional link "gain" is realized on 70 cm because lower levels of man-made noise reduce implementation loss. While Table 1 shows that stations with 0-dBi antennas would not be able to access the satellite (at the reference BER), stations without antenna-pointing capability could use fixed-pointing gain antennas aimed at high elevations. Thus, using a 70-cm downlink is a possible option for PACSAT and should be explored. To simplify the following discussion, however, we assume that the downlink will be in the 2-meter band.

2.2 Uplink Budget

Whilst free-space loss may make it desirable to keep all PACSAT communications on the lowest frequency available (2 meters), we have discarded this notion for an amateur spacecraft. The state-of-the-art in amateur radio does not easily allow simultaneous transmission and reception within the same band. Receivers do not have enough immunity to front-end overload and transmitters produce wide-band phase noise. The option of having both uplinks and downlinks at VHF might,, nonetheless, be investigated for a store-and-forward satellite operating in some commercial service, where the cost of purpose-built equipment could be justified. In the amateur service we must consider the equipment at hand, and recommend that the uplink be in the 70-cm band, assuming that the downlink is at 2 meters.

Again, we are faced with the 9.5 dB difference in path loss between 2 meters and 70 cm. We assume that, by using methods discussed below, we will be able to make uplink demodulators about 2 dB more efficient than those on the downlink.

Path loss difference between 70 cm and 2 m.	-9.5 dB
Increased efficiency of spacecraft demodulators.	2 dB

Difference between 2-m and 70-cm power budgets.	-7.5 dB

As a point of reference, using uplink antennas having the same gain as downlink antennas (8.2 dBi), the groundstation will need 7.5 dB greater EIRP on 70 cm than the satellite needs on 2 meters, resulting in a requirement for 14 watts transmitter output. This will result in horizon-to-horizon coverage at 9600 bit/s, with BER less than 1E-6. Again, stations with fixed antennas, lower antenna gain or lower output power would be able to access the satellite at higher elevations or with increased BER.

3.0 MODULATION AND DEMODULATION

Signal-to-noise ratios such as we have been discussing (73 - 15 dB) would produce the desired BER of 1E-6 in systems employing any of several modulation methods. Among the choices are frequency-shift keying (FSK), minimum-shift keying (MSK) and differential phase-shift keying (DPSK). DPSK is described in [3] and has previously been proposed as the modulation method for PACSAT. The major disadvantages of DPSK are that once it has been filtered for bandwidth efficiency it cannot be amplified by limiting amplifiers, and that it requires the use of complex synchronous receivers and transmitters. We propose the use of noncoherent FSK on the uplink and coherent FFSK on the downlink. Noncoherent FSK is simply the technology investigated by S. Goode [4] -- transmitter VCO control voltage is derived from filtered baseband data. Coherent FFSK requires that the phase of the RF signal be strictly controlled, requiring a transmitter more complex than the simple groundstation transmitter. There is, however, an important advantage to using coherent FFSK rather than DPSK: coherent FFSK can be demodulated by simple, non-coherent receiver/demodulators.

3.1 General Uplinks

We propose that groundstations use non-synchronous FSK with a optimum deviation of 3.2 kHz. Modulators would be based on S. Goode's system [4] The data rate will be fixed at 9600 bit/s, and the IF bandwidth of limiting amplifiers fixed at 15 kHz. Receivers on the spacecraft would feed plain quadrature frequency discriminators followed by filters and slicers -- again as in Goode's system. This may seem a technically regressive step, but the very considerable pressures on reliability and power consumption onboard the spacecraft always tend to favor the simplest solution. It is hoped that by developing post-discriminator filters that reduce or eliminate inter--symbol interference, we could realize a 1E-6 BER with uplink signals as low as 13 dB Eb/No. We intend to investigate this in the lab as soon as possible.

The choice of non--coherent FSK for the uplink makes the groundstation modulator/ transmitter relatively simple. It also satisfies the desire to have the 9600-bit/s signal fit in the 15-kHz bandwidth of a standard IF. On the 70-cm uplink, maximum Doppler shift will be +/- 10 kHz, and without compensation, this much shift will cause demodulation to fail. We propose that the groundstation be responsible for tracking uplink Doppler to within roughly 500 Hz. In selecting uplink channels, we shall endeavour to provide wide enough spacing that if one groundstation does not correctly track Doppler shift, its transmissions will not drift adjacent uplink channels. Uplink channel spacing of 50-kHz should provide this protection..

There are, of course some disadvantages to using such a simple scheme. First of these is that stations with marginal links cannot decrease their BER by simply decreasing their bit rate. For such a speed reduction to have the desired effect, the IF bandwith of the uplink receivers would have to be narrowed. The complexity of variable-bandwidth receivers is not acceptable. The only way to increase throughput on these links is to resort to forward error correction (FEC) and take advantage of coding gain. P. Sweeney of UoS has investigated simple FEC schemes for store-and-forward satellites. His work indicates that an array code based on two Hamming structures could restore an uplink error rate of 2E-3 to our reference standard 1E-6 BER. His proposed code reduces the data rate to 6600 bit/s (with a signalling rate of 9600 bit/s) and reduces the Eb/No requirement by 3.6 dB. This is a significant benefit to the overall system, allowing the transmitter power to be more than halved.

The other disadvantage to employing simple discriminator demodulators on the satellite is that they are not upward compatible with such desirable types of modulation as Tame FM (also known as Generalized Minimum Shift Keying, GMSK).

3.2 Uplink Enhancements

Given sufficient time, we hope to complete an investigation into a more complex uplink decoder, employing the delay demodulators discussed in [5]. These ingenious demodulators require no clock or carrier recovery, should be highly tolerant of Doppler shift, and could provide virtually the same performance as more complex synchronous decoders (11 dB Eb/No for 1E-6 BER). To take advantage of this enhanced uplink decoder, the groundstation would reduce deviation to +/- 2.4 kHz, but would not have to resort to a coherent transmitter. Unlike a simple quadrature discriminator, a delay decoder could realize decreased BER at lower bit rates (given a fixed groundstation power) without altering receiver IF bandwidth. The uplink signal could still be generated by a Goode-type modem, as it need not be synchronous. Groundstations that do not reduce their deviation will get the same performance that they would have from simple quadrature discriminators. The limitation of the delay decoder is that it is STILL a frequency discriminator and cannot work on Tame FM/GMSK.

3.3 Research Uplink

Given even more time (and satellite power), we propose to have a "research" uplink for experimentation with synchronous, highly-efficient modulation methods. This uplink would use a De-Buda type synchronous receiver [6] requiring clock and carrier recovery. Stations using such the uplink would HAVE to have phase-controlled coherent transmitters. These increases in complexity are rewarded by the ability to use Tame FM/GMSK and send 14,400 bit/s within the 15-kHz uplink channel. The research uplink would not detract from the PACSAT mission, as the general uplink channels would always provide a standard, predictable service to the user. The research uplink could, however, aid us in the necessary search for higher throughput and provide enhanced service to the advanced user.

3.3 Uplink Summary

We propose that the uplink employ non-synchronous FSK. If spacecraft decoders use straightforward quadrature discriminators, the optimum transmitter deviation is +/- 3.2 kHz. Provided that delay-type demodulators can be developed for the spacecraft environment, groundstations using +/- 2.4 kHz deviation (FFSK) would realize 2 dB advantage over those using other deviations. As a point of reference, a station transmitting 14 watts FSK into an 8.2-dBi antenna would have a BER less than 1E-6 from horizon to horizon. A station with omnidirectional antennas would achieve the same BER while the satellite was above 30 degrees elevation and experience degradation (see Table 1) at lower elevations. Both FEC and transmission-rate reduction should be investigated as ways of providing lower BER to marginal stations. A research uplink, whilst not detracting from the mission, could provide an invaluable tool for development of efficient, high-speed signalling methods.

4.0 DOWNLINKS

It has been demonstrated in the literature [7] (and it has become painfully apparent to packet-radio users on crowded channels) that multiple stations contending for a single communications channel drastically reduce channel efficiency. Thus, as RUDAK [8] serves a 2400 bit/s uplink with a 400-bit/s downlink, PACSAT will be able to serve four or five 9600-bit/s uplinks with a single 9600-bit/s downlink. The modulation method chosen for this downlink must be power and bandwidth efficient and it must yield reasonable results to unsophisticated groundstations. It would also be advantageous if users willing to invest in sophisticated decoders could expect to get better performance for their effort. To fill these requirements, we recommend coherent FFSK, also known as "fast frequency shift keying with spectral modification using non- linear filtering." The deviation at 9600 bit/s will be +/- 2.4 kHz.

The complexity of coherent transmitters is such that we do not wish to insist that users have them. We can, on the other hand, afford the effort to build a few such transmitters for the satellite. Coherent FFSK is bandwidth efficient (again we can easily fit 9600 bit/s into 15-kHz) and it produces a constant-envelope signal which can be passed through efficient limiting amplifiers without bandwidth spreading. This is an important consideration when choosing a modulation method for the satellite.

If the satellite transmits coherent FFSK, the user is presented with a range of potential receiver/decoders and an accompanying range of performance. The groundstation need not use a synchronous demodulator - adapted narrow-band FM receivers with discriminator decoders would require 15 dB Eb/No for 1E-6 BER. Delay-type demodulators (theoretically simple to construct) and sophisticated synchronous receiver/decoders should lower this requirement to around 11 dB -- a valuable gain of 4 dB. This is precisely the type of upgradable system that we desire in an amateur-radio operation.

4.1 Research Downlink

We propose that PACSAT carry a research downlink for ongoing experimentation with high-speed, high-efficiency signalling methods. On first consideration, one assumes that if the satellite could power two downlinks, we would be able to double the power on our general downlink. The research downlink, however, would not have the 100 percent duty cycle of the general downlink. It would be turned on only for experiments or for limited "sophisticated user" service. Groundstations using this downlink would have to have synchronous decoders. The data rate could reach 14,400 bit/s within 15 kHz bandwidth or 19,200 bit/s in a 20-kHz bandwidth. To do this we would employ a tighter form of non-linear premodulation filtering -- changing the modulation to "tame FM" (also called Generalized Minimum Shift Keying, GMSK).

4.3 Downlink Summary

Coherent FFSK can be efficiently generated and amplified on the satellite, and provides the users with a wide range of potential decoders. With even a simple discriminator decoder, a user with an 8.2 dB gain receive antenna could get horizon-to-horizon coverage, while a user with an omnidirectional antenna would get the reference BER of 1E-6 whenever the satellite was above 30 degrees elevation. We would like to experiment with Tame FM (GMSK), which would allow us to increase bit rate by half without increasing uplink bandwidth. Such research should be accornodated in the final PACSAT design.

5.0 DOPPLER TRACKING

In the assumed 900 km orbit, maximum Doppler shift at 2 meters is +/- 3.5 kHz, and at 70 cm it is +/- 10 kHz. While some frequency error between transmitter and receiver has been accounted for in the link calculations under implementation margin, we believe that error much greater than 500 Hz should be avoided. We need to do further research to support this claim. The coherent FFSK proposed for the downlinks can, with suitable data randomization, yield a DC-free baseband signal. Any dc level on the demodulated signal would then indicate frequency error. This dc "error signal" becomes the basis for Doppler tracking.

It was originally proposed that the uplink receivers track Doppler shift, allowing the user to set his transmitter anywhere in a wide uplink channel and not change frequency over the course of a pass. We recommend that this technique be discarded. Our recommendation is based on the following scenario: Imagine that two users, one "in front of" the satellite and the other "behind" the satellite are both sending packets on the same uplink channel. One of these users is seeing nearly +10 kHz Doppler shift, while the other sees nearly -10 kHz Doppler (in the worst case). If the uplink receiver is responsible for Doppler tracking, on alternating packets it will have to swing 20 kHz to lock on the necessary signal. As far as we can tell from the literature and from personal contacts, no one has been able to track this much instantaneous frequency shift at a data rate near 9600 bit/s. If we were to use AFC loops with such bandwidth, they would probably take hundreds of bit periods to lock up, cutting into precious uplink communication time.

We propose that the groundstation be responsible for tracking Doppler shifts. If the station is computer-controlled, the computer can easily produce Doppler information in analog or digital form for the uplink transmitter. If the station is not computer controlled, the downlink receiver must already have some closed-loop Doppler-tracking mechanism, which could feed a tracking signal to the uplink transmitter. For the groundstation receiver, tracking the spacecraft is a relatively easy task. The groundstation sees a smooth Doppler shift over the course of a pass, not the rapid switching that would have to be tracked by the satellite. Development of suitable groundstation receivers and transmitters should, we believe, be undertaken or at least coordinated as part of the PACSAT project.

6.0 ADAPTIVE COMMUNICATION

Notwithstanding that the realization of a single-speed, 9600-bit/s, space-engineered communications system will be a major task, we propose that PACSAT have an optional reduced data rate to accomodate poor links and/or an optional high data rate for especially good links. The importance of these options can be understood by studying Table 1. For our proposed PACSAT orbit, the free-space path loss is 12 dB less when the satellite is overhead than when it is at the horizon. A station with steerable antennas, equipped to communicate with the satellite at low elevation angles will have 12 dB "extra" link margin when the satellite is overhead. This extra margin could easily accomodate an increased data rate while the satellite is high in the sky. The free-space loss profile of the satellite-groundstation link allows stations with omnidirectional 0-dBi antennas to the satellite when it is 30 degrees or more above the horizon, but this is not the most efficient solution for stations with fixed antennas. These stat-ions need antennas adapted to the link profile --- 8 dBi on the horizon and down to -3 dBi overhead. Alternatively, a station equipped with high-speed encoders and decoders could USC a directional antenna fixed at a high elevation, communicating all of its traffic in a bandwidth-efficient manner when the satellite was closest. Such adaptive communications are well suited to the packet-radio environment, in which administrative messages can be communicated between satellite and groundstation without disrupting other communications. Users may be able to "bargain" with PACSAT for an increased or decreased communications rate.

7.0 CONCLUSION

Presented here are some thoughts concerning PACSAT design. Our recommendations are NOT official PACSAT design decisions. They are presented to give users some idea of how we arrive at design decisions, to give all-ly idle technicians some things to implement, and to allow those with opinions on these rnatters to express those opinions. We cannot hope to decide today what will be the best modulation methods available in the future, but we think that FSK and FFSK will provide PACSAT with the communications tools needed to carry out its mission. The proposed combination of coherent and non-coherent methods should provide a smooth transition between the relatively slow data communications available to amateurs today and the fast communications that will have to become available in the near future.

8.0 ACKNOWLEDGMENTS

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TABLE 1 - PATH LOSS and REQUIRED GAIN VS. SATELLITE ELEVATION

El.	Path Loss	Gain on 2 meters	Gain on 70 cm.
0	146.6	8.2	17.9
10	143.9	5.5	15.0
20	141.5	3.1	12.6
30	139.5	1.1	10.6
40	137.9	-0.5	9.0
50	136.7	-1.7	7.8
60	135.8	-2.6	6.9
70	135.2	-3.2	6.3
80	134.9	-3.5	6
90	134.8	-3.5	6

(1) Elevation of satellite in degrees.
(2) Free space loss at 2 meters.
(3) Gain (dBi) necessary to achieve 1E-6 BER on 2-meter downlink.
(4) Gain (dBi) necessary to achieve 1E-6 BER on 70-cm downlink.

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