

FQPSK DEVELOPMENTS RECOMMENDED FOR CCSDS STANDARDIZATION BY NASA JPL

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ABSTRACT

In 1992, international space agencies became concerned that increasing frequency band congestion, together with attempts by the mobile telephone industry to obtain additional bandwidth, would result in substantially more interference incidents. The CCSDS undertook a technical study to identify and recommend more bandwidth efficient modulation schemes, which would permit more users to co-exist in a frequency band while reducing interference incidents. This paper describes the contribution of the Jet Propulsion Laboratory (JPL) to that effort.

KEY WORDS

Modulation, Feher's quadrature phase shift keying, bandwidth, efficient, CCSDS, and efficiency.

INTRODUCTION

At their Fall 1992 meeting, the Space Frequency Coordination Group (SFCG) reviewed results from the 1992 World Radio Conference (WRC). The SFCG comprises spectrum managers from more than 30 space agencies engaged in scientific research around the world.

SFCG members were concerned because the mobile telephone community had sought reallocation of the 2 GHz frequency bands for Personal Communication System (PCS) use. The space science community had relied on these bands since the 1960s for communications between spacecraft and Earth stations. Sharing these bands with individual PCS users posed an impossible coordination burden and success by the mobile industry at the 92 WRC would have meant the loss of billions of Dollars in infrastructure investment by space agencies.

Additionally, congestion in the 2 GHz band had been increasing dramatically with a concomitant increase in interference events. Realizing that it was only a matter of time until the space science community was forced to operate with significantly less bandwidth, either as a result of increased congestion or loss of a portion to the PCS industry, the SFCG asked the Consultative Committee for Space Data Systems (CCSDS) to investigate means for improving their bandwidth utilization efficiency.

Formed in the early 1980s, the CCSDS also comprises more than 30 member and observer space agencies plus and additional 150 industrial partners. Their objective is to develop technically sophisticated standards to facilitate the exchange of data among space agencies. One CCSDS Subpanel (Radio Frequency and Modulation) accepted the SFCG challenge and agreed to undertake a study to identify the most bandwidth efficient modulation methods, which would meet the criteria established by the SFCG.

CCSDS EFFICIENT MODULATION STUDY

Guidelines for the study were provided to the CCSDS by the SFCG. They stated that any modulation type recommended for adoption as a standard should:

- Increase RF spectrum utilization efficiency, permitting more users to operate in the band.
- To the extent possible, be compatible with equipment used by the space agencies.
- Not increase the end-to-end losses by more than about 1 dB relative to unfiltered BPSK.
- Have flexibility so that users can change data rates without incurring expensive retesting.

Many organizations contributed to this international CCSDS study. In alphabetical order they included:

- Aerospace Corporation (ASC)
- Centre National d'Etudes Spatiales (CNES, study participation began in 1998)
- European Space Agency (ESA)
- NASA Goddard Space Flight Center (GSFC)
- Jet Propulsion Laboratory (JPL)
- New Mexico State University (NMSU)

Some focused on one or two modulation methods (ASC, CNES, GSFC, NMSU) while others examined a broad spectrum of modulation types (ESA, JPL). The CCSDS mandate is clear: *to be accepted as a recommended standard, a proposed guideline must be based on sound engineering principles and represent the consensus of the member and observer agencies.*

JPL's PHASE 3 EFFICIENT MODULATION METHODS STUDY

This paper focuses on JPL's investigation because of the Author's familiarity with that work and the study's comprehensive nature. The study included some 13 different modulation types.

Work on the *CCSDS-SFCG Efficient Modulation Methods Study at NASA/JPL* progressed through several stages:

- Phase 1: A Comparison of Modulation Schemes*
- Phase 2: Spectrum Shaping*
- Phase 3: End-to-End System Performance*
- Phase 4: Interference Susceptibility*

JPL's PHASE 3 MODULATION METHODS STUDY

In Phase 3, JPL concluded that baseband filtering was the only viable option for controlling spectral emissions. A simple filter substitution can be made if the data rate is changed. Unlike intermediate frequency (i.f.) and post power amplifier filtering, base band filtering eliminates the need for re-qualifying the Radio Frequency Subsystem (RFS) when it is used on subsequent missions having different data rates.

Based principally on the ESA and JPL studies, the SFCG adopted spectrum emission masks (Figure 1). Selection depends upon whether the data rate is above or below 2 Msps..

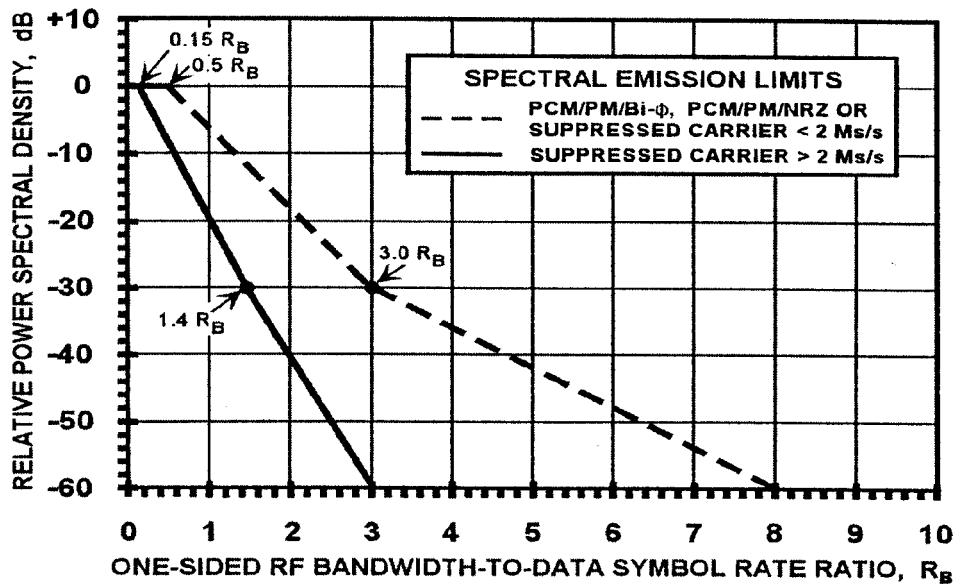


Figure 1: SFCG RF SPECTRUM EMISSION MASKS

Having provided the technical studies leading to the masks in Figure 1, the CCSDS needed to identify one or more modulation schemes that would meet their requirements. JPL's Phase 3 Study report defined *Spectrum Improvement Factor* as the ratio of the spectral bandwidth of unfiltered BPSK (reference) to the spectral bandwidth of each modulation type studied, measured in 10 dB increments below the peak of the envelope. Figure 2 shows the results.

From Figure 2 it is clear that FQPSK-B is some 150 times more bandwidth efficient than unfiltered BPSK, when the measurement is made at 50 dB below the peak of the spectral envelope. Because of variations in orbital distances and E.I.R.P.'s, a comparison at 50 dB below the spectral peak is appropriate for Earth orbiting scientific spacecraft. Three candidates were evident from JPL's and ESA's Phase 3 studies (in order of bandwidth efficiency):

- FQPSK-B (Feher's patented quadrature phase shift keying)
- GMSK (Gaussian Minimum Shift Keying, $\alpha = 0.25$)
- Highly Filtered OQPSK (filter BTs ≤ 1.2)

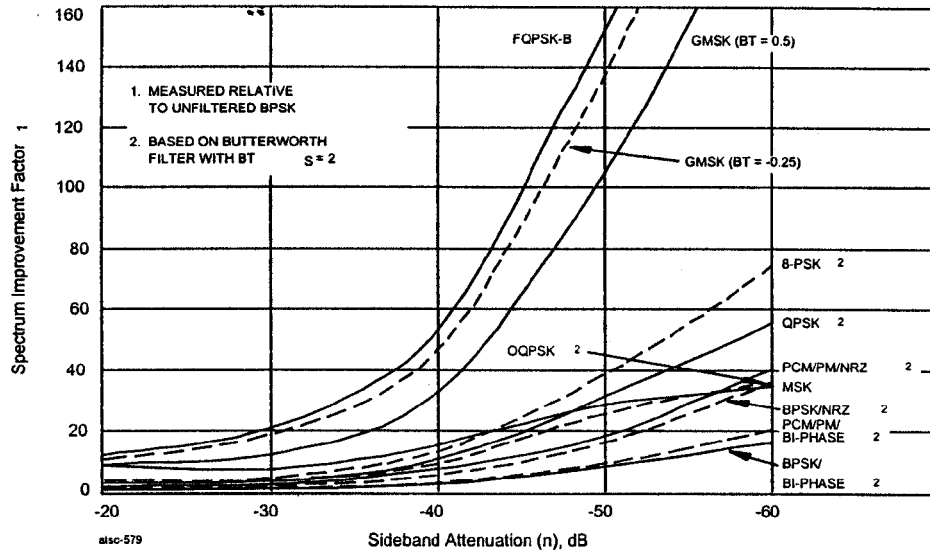


Figure 2: Spectral Efficiencies

While moderately bandwidth efficient, 8-PSK modulation was not a viable candidate because its end-to-end system losses substantially exceed the criteria established by the SFCG.

In 1997, little was known in space science community about the two most bandwidth efficient modulation schemes, FQPSK-B and GMSK. For FQPSK-B, the problem was exacerbated by a lack of knowledge about key parameters, which frustrated international efforts to study the modulation scheme. JPL (California Institute of Technology) entered into a Technical Cooperation Agreement with Digcom Inc. making those trade secrets available. Therefore, JPL was responsible for characterizing FQPSK-B's end-to-end system's performance.

Likewise, little was known about GMSK except that it is widely used in cellular telephones. The Aerospace Corporation undertook an in-depth study of this modulation type.

Some believed filtered OQPSK was the best choice because it could be captured using a standard OQPSK receiver, which most space agencies already have in their networks. However, other space agencies were unconvinced because its relative bandwidth inefficiency caused problems in meeting the SFCG's spectrum mask. Furthermore, it was difficult to generate without introducing discrete spectral components or spectral re-growth. Little was done after 1997 to investigate filtered OQPSK. A few did not realize the FQPSK-B also uses an OQPSK receiver.

JPL's PHASE 4 EFFICIENT MODULATION METHODS STUDY

Several members of the CCSDS RF and Modulation Subpanel speculated that a modulation method having a narrow spectral bandwidth would be more susceptible to interference than a modulation scheme producing a wider spectrum. This generalization seemed to spring from a belief that spread spectrum is comparatively immune to interference. Phase 4 quantified the interference susceptibility of the three modulation types listed above.

Two types of -interference were investigated on a victim receiver capturing the modulation type under investigation, which, employed a matched filter. Narrowband interference was taken to be a single line (as with an unmodulated RF carrier) having a variable E.I.R.P. with respect to the victim. Conversely, a Wideband interferer assumed to be an unfiltered BPSK signal with the same data rate, and a variable E.I.R.P. Both interferers were placed far from the victim's center frequency, f_v , and then shifted towards f_v , while measuring the degradation to the victim. The resulting plots show degradation to the victim as a function of the interferer's frequency offset. Figure 3 is an example of FQPSK-B's susceptibility to narrowband interferer.

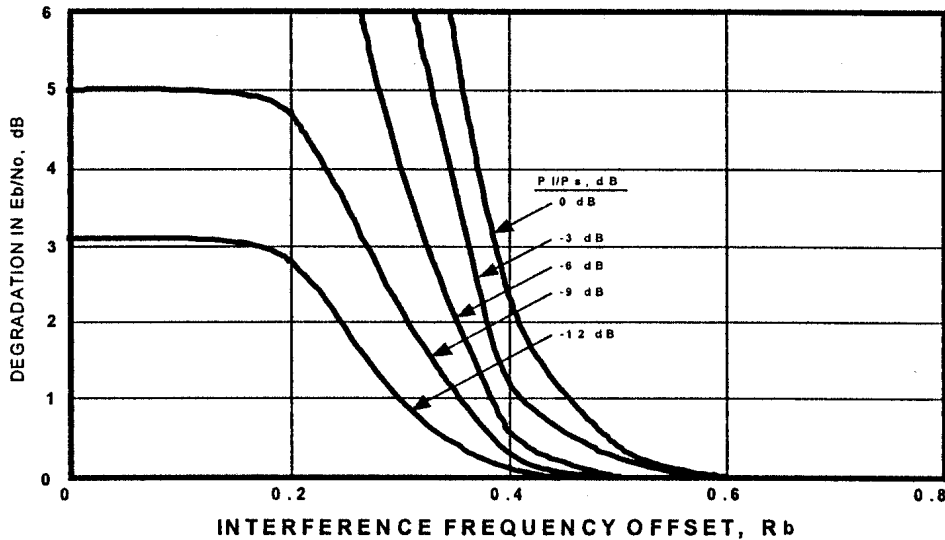


Figure 3: FQPSK-B Susceptibility to Narrowband Interference

With an interferer whose spatial location and E.I.R.P. are identical to the victim's, no degradation is found until the center frequency separation between victim and interferer is less than $0.6 R_B$ (where R_B is the victim's data rate). 1 dB of degradation occurs at about $0.45 R_B$. Comparing with unfiltered BPSK under the same conditions, it was found that the same degradation occurs at approximately three times the separation between victim and interferer.

To compute the necessary frequency separation between user spacecraft operating in the same frequency band, consider the case of two spacecraft orbiting the Earth in the equatorial plane as shown in Figure 4. Spacecraft 1 is at a constant altitude above the Earth's surface of 6.7×10^4 km. The other (spacecraft 2) is in a highly elliptical orbit with an apogee of 1.8×10^6 km and a perigee equal to the altitude of spacecraft 1. For simplicity, assume both spacecraft have equal data rates, modulation types, Bit-Error-Rate (BER) requirements, and therefore, RF spectra.

Occasionally, both spacecraft will fall into the beamwidth of a single Earth station. If the frequency separation is insufficient, interference will result. Since the BER required of both missions is the same, the telemetry power spectral density (E_B / N_0) for the two spacecraft should be the same when each are at their maximum distance. That will be the case when spacecraft 1 is at 6.7×10^4 km and spacecraft 2 is at its apogee of 1.8×10^6 km.

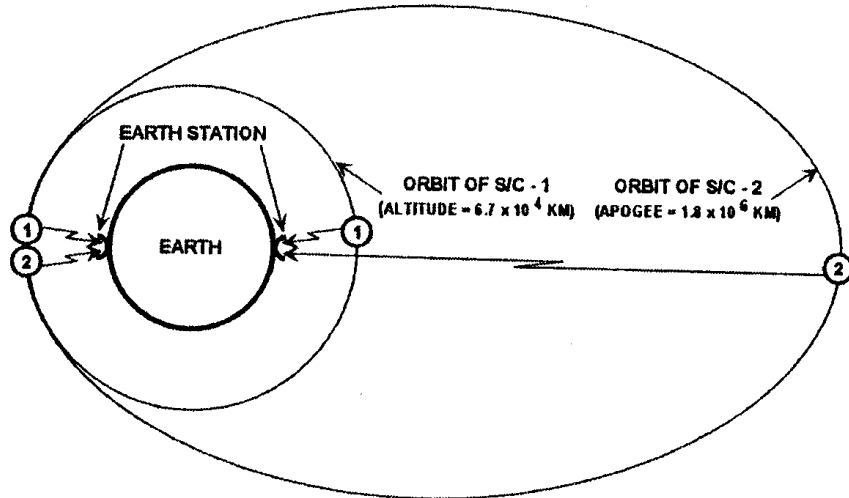


Figure 4: Interfering Spacecraft

Very few space agencies change spacecraft transmitter power and when spacecraft 2 is at its perigee of 6.7×10^4 km, its power spectral density will increase by 29 dB. Moreover, some agencies do not specify spacecraft transmitter power based upon each mission's specific needs. Rather, they purchase power amplifiers in the discrete power levels offered by the manufacturer. This can produce an excess E_B/N_0 of up to 10 dB over that required for the desired BER.

To avoid excessive degradation from a spacecraft operating on an adjacent channel, Figure 3 indicates that the RF spectra should not be permitted to intersect the main spectral lobe (approximately $\pm 0.5 R_B$ for FQPSK-B). This point is at about 20 dB below the spectral peak.

To avoid interference when the two spacecraft shown in Figure 4 are within the same beamwidth, the minimum center frequency separation between the two transmitters is found by determining the level at which the spectrum of the stronger signal (spacecraft 2) is permitted to intersect that of the weaker one (spacecraft 1). Adding the numbers above gives that level.

Table 1: Required Sideband Attenuation

Required dB	Resulting From:
29	Change in Earth Station-S/C Distance
10	Transmitter Power Variation
20	Maximum Permitted Spectral Intersection
59	Total Required Sideband Attenuation

Table 1 shows that, if degradation to a spacecraft with a weaker signal (spacecraft 1), operating on an adjacent channel, is to be 1 dB or below, the spectrum of the stronger signal (spacecraft 2) must not intersect

the spectrum of the weaker signal (spacecraft 1) until it is at least 59 dB below the peak of the stronger signal. Thus, it is important to have a modulation method whose spectrum is both narrow and whose sides are very steep.

FQPSK-B has the required spectrum. Figure 5 is a plot of an actual FQPSK-B transmitted spectrum, measured at 8.4 GHz using real hardware, in JPL's Telecommunications Development Laboratory.

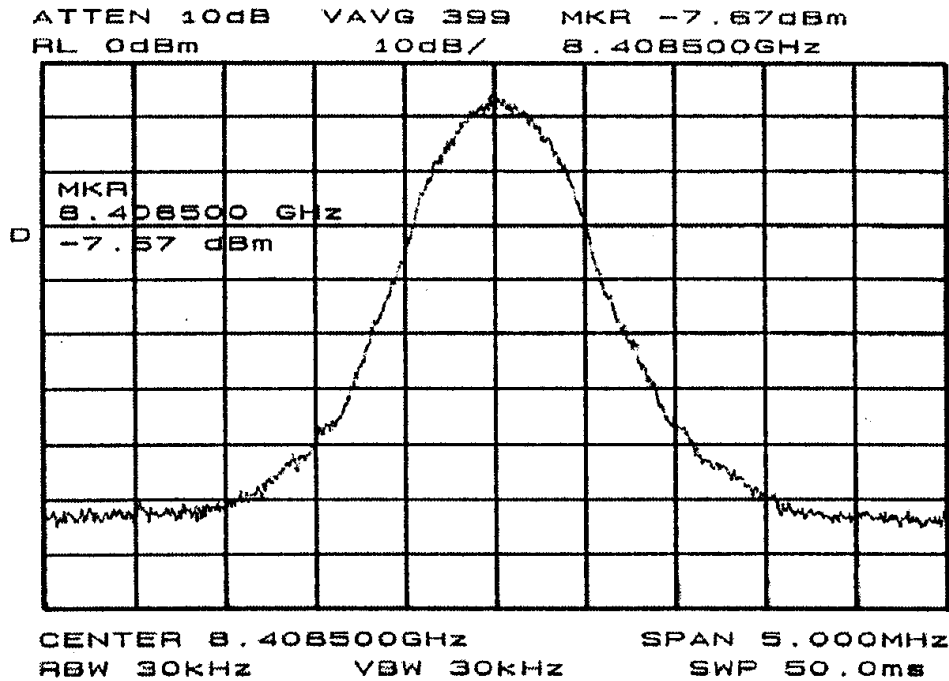


Figure 5: FQPSK-B Spectrum

Figure 5 shows the FQPSK-B spectrum to be 60 dB below its peak at $\pm 1 R_B$ ($\pm 1 \times$ the data rate). Therefore, it should be possible to locate adjacent channels at a frequency of approximately:

$$F_s = \frac{S/C-1 \text{ DATA RATE}}{2} + \frac{S/C-2 \text{ DATA RATE}}{2}$$

Such a system should only suffer a modest degradation from adjacent channel interference. Only FQPSK-B and possibly GMSK (BT = 0.25) were found to permit this close channel spacing.

CONCLUSIONS OF JPL's EFFICIENT MODULATION METHODS STUDIES

JPL concluded that FQPSK-B was that best choice for a CCSDS Recommended Standard because it was determined to:

1. Embody the most bandwidth efficient spectrum of the modulation types evaluated.
2. Have acceptable end-to-end losses.

3. Be comparatively simple to generate.
4. Require only baseband filtering (no post power amplifier filtering required).
5. Need only a conventional OQPSK receiver for efficient capture.
6. Possesses good immunity to interference from other users in the frequency band.

Accordingly, JPL has recommended that the CCSDS consider adopting FQPSK-B as a recommended modulation method for high data rate Earth orbitin missions.

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