# Spectral Distortion in High Data Rate Remote Sensing Satellite Links

By V. Sambasiva Rao and Surendra Pal
ISRO Satellite Centre

This article describes how data rate, data coding, modulation type and circuit design choices affect the spectral distortions (carrier suppression and spurious responses) in a satellite link

Remote Sensing satellites of today are being configured with state of the art imaging sensors to provide very high resolution imageries, demanding very high bit rate data transmission. The design of the system becomes more complicated with increasing data rates. With those increased data rates, spectrum usage and channel bandwidth has become more stringent to conserve spectrum and to assure optimum data transmission capability.

A primary consideration for the design of satellite communication systems is efficient use of transmitted power and channel bandwidth, as space communication links are both power and bandwidth limited. This led to the search for a wide variety of techniques, such as new allocations at higher frequencies, frequency re-use, spectrally efficient modulation techniques and efficient source coding techniques for optimum onboard power usage. A final requirement is the study of the implications of implementing the new techniques.

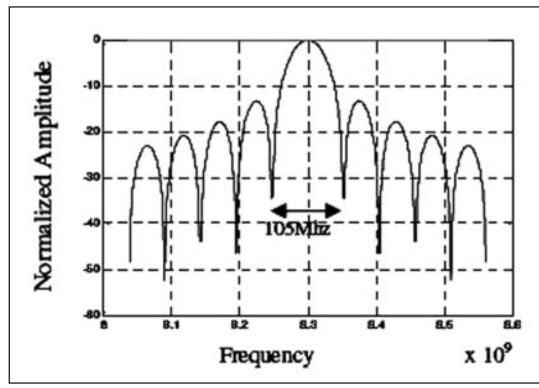


Figure 1 · An ideal QPSK spectrum.

## Frequency Bands and Modulation Types

For space to earth data transmission, frequency spectrum of about 20 MHz in S-band, 375 MHz in X-band and 1500 MHz in Ka band is allotted. Each has differing requirements to meet the most important objectives of satellite communications: power and bandwidth/spectrum efficiency, combined with robust Bit Error Rate (BER) performance in a strong interference environment.

Various modulation techniques [1, 2] have been explored to handle higher data rate in the available bandwidth. Several modulation techniques such as conventional binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), offset quadrature phase shift keying (OQPSK), also designated as staggered quadrature phase shift keying (SQPSK) and multi-phase shift keying, such as 8-PSK, techniques including differential encoding variations of the same are considered for high bit rate data transmission. The RF spectral efficiency of the above mentioned systems for four state modulation systems, such as QPSK, is limited to 2 b/s/Hz, while the spectral efficiency of multi-ary systems such as 8-PSK and 16-PSK are limited to 3 b/s/Hz and 4 b/s/Hz. An increased number of signaling states increases the complexity of a transceiver and increases the required C/N, meaning that it has a negative impact on the BER = $f(E_b/N_0)$ performance, as increased C/N requirement and increased $E_b/N_0$ requirement leads to more expensive and larger transceivers and/or reduced margins. Such a relatively high spec-

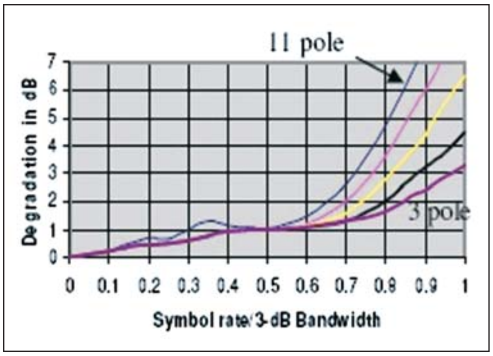


**Figure 2 · Bandwidth limiting degradation of QPSK signals.**

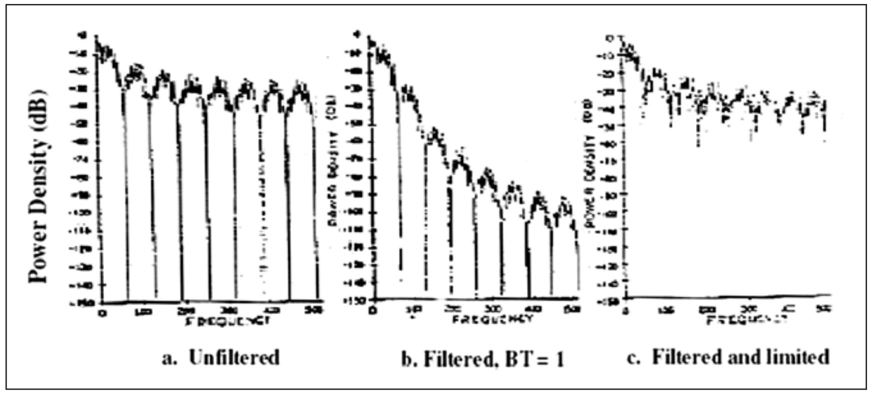


**Figure 3 · Power spectra of QPSK signal with filtering and limiting.**

tral efficiency requires complex implementations, steep filters and a significantly increased C/N requirement.

QPSK modulation, being the optimum modulation technique in terms of spectral and power efficiency is used for most of the Remote Sensing Satellites to date. It is planned to transmit data of 640 Mbps at X-band with QPSK modulation in dual polarization in one of the near future remote sensing satellites of Indian Space Research Organization (ISRO). However, the quest for obtaining better resolution imagery demands the transmission of higher bit rate data beyond 640 MBPS, necessitating the use of high order modulation techniques as well. With high data rates, the modulated spectrum is getting distorted and deviating from theoretical (sin$x$)/$x$ pattern. Various factors affecting the spectrum and their effects are discussed in the following sections.

The satellite system is basically configured based on the RF link performance estimation which in turn depends on the modulation technique, data rate which is limited by the available channel bandwidth, figure of merit (G/T) of the ground station and onboard Effective Isotropic Radiated Power (EIRP).

First, major factors limiting high bit rate data transmission include: The power spectral density of an unfiltered BPSK signal when carrier $f_c$ is modulated by NRZ random data is given by

$$s_i(f) = 2.k.A^2.Tb.\left[\frac{Sin(\pi.(f - f_c).Tb)}{(\pi.(f - f_c).T_b)}\right]^2 \qquad (1)$$

The QPSK signal is generated by linear addition of two quadrature (one shifted by 90 deg.) BPSK signals which can be represented as

$$S_{\mathrm{qpsk}}(f) = S_i(f) + j.\,S_i(f) \qquad (2)$$

For random equiprobable input data, equation (2) represents the power spectrum of unfiltered QPSK modulation. Figure 1 shows a typical unfiltered ideal RF spectrum of an X-band carrier modulated with 105 Mbps randomized data.

## Bandwidth

Theoretically, the RF spectrum with (sin$x$)/$x$ distribution occupies infinite bandwidth. It is essential to limit the radiated spectrum to the minimum possible bandwidth. The spectrum can be restricted by pre-modulation filtering of the data and also by band-limiting the transmission channel. In practice, the data can be demodulated by restricting the QPSK spectrum to a bandwidth of 0.6 times the data rate. The effect of this filtering is to degrade system performance due to both filtering distortion and the associated inter-symbol interference. It is important to determine the system performance degradation and trade off involved with the use of filters (see Figure 2).

To compensate for the degradation due to band limiting, the only means is to increase onboard EIRP as G/T is more or less fixed at the ground stations. The spectrum can also be filtered at the post-amplification stage before transmission but this is associated with more power loss. To save the onboard power the spectrum can be limited prior to power amplification, however, if the filtered signal is amplified by a nonlinear amplifier, the spectrum must be restored, as can be seen from Figure 3.

To avoid spectrum restoration, highly linear power amplifiers are needed. Linearized amplifiers are less RF power efficient and expensive. Since, available power onboard spacecraft is premium; it is general practice to transmit one full main lobe of the spectrum which constitutes 90% of the total power with which the degradation due to band limiting is negligible. To meet the stringent radiation level limitations in the adjacent band of the Deep Space Network, the transmitted signal shall be filtered sufficiently before transmitting. The filter shall be of low loss, and at the same time shall provide acceptable rejection outside of the allotted band. It is currently practical to realize bandpass filters to transmit up to 320 Mbps QPSK modulated data in the allotted 375 MHz bandwidth, with low insertion loss in the passband and sufficient rejection out of the passband.

## Data Quality

The data of the imaging sensors on board remote sensing satellites is formatted, randomized to avoid continuous states of 1 or 0 in the data (which is an essential requirement for clock recovery in the demodulation process) and differentially encoded to avoid phase ambiguities and assure correct demodulation of the data. The active elements used in handling the data before modulation are limited in frequency of operation. More over, due to various size and location limitations on the satellite, the image sensing system, base band data handling systems, RF systems including modulators, power amplifiers and transmitting antennas are accommodated with spatial separation. The data from baseband systems is fed to modulator through coaxial cables. The parasitic reactance (e.g., capacitance of coaxial cable) effects the rise/fall time of the data and also duty cycle. The switching will have different turn ON and turn OFF times due to diffusion capacitances. All parasitic reactances will spoil the shape of the data pulse. The waveform can be approximately represented by trapezoidal pulses as shown in Figure 4.

Poor rise time and/or fall time will affect the modulated RF spectrum, an effect that can be simulated. Equation 1 gets modified for the power spectrum for antipodal PSK modulation [1] by data with waveform period $T$, rise and fall times $s$, there by the top of the pulse having width $\tau = T - 2s$, as

$$G(f) = \frac{T}{4}\left(\frac{\pi}{4}\right)^2 \left\{ \frac{\dfrac{\tau}{T}\dfrac{Sin\pi(f_c - f)\tau}{\pi(f_c - f)\tau} + \dfrac{s}{T}\cos\pi(f_c - f)T}{\left[(f_c - f)s\right]^2 - \left(\dfrac{\pi}{4}\right)^2} \right\}^2$$

where $f_c$ is carrier frequency.

The simulated spectrum is shown in Figure 5. The spectrum has small discrete line components because of the DC content, which is due to unequal top and bottom parts of the waveform as well as data asymmetry. The amplitude of the discrete spectral components increases with the average DC content in the data.

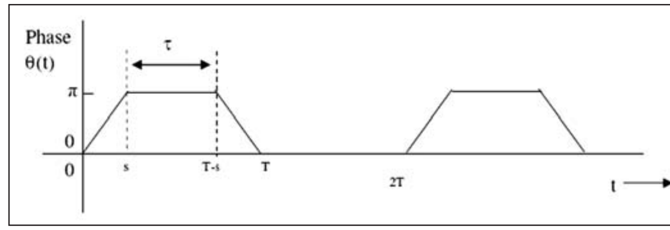


Figure 4 · Data pulses of BPSK phase finite rise/fall time.

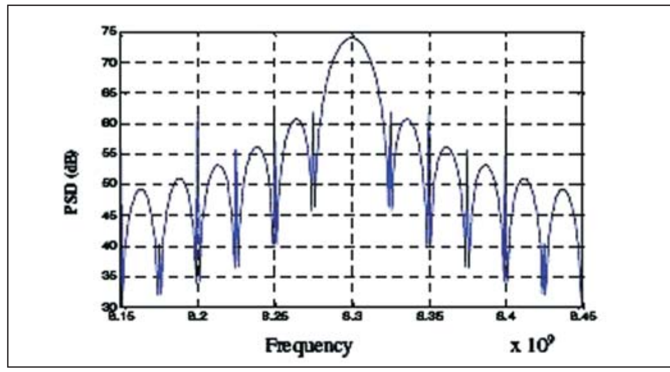


Figure 5 · Power spectrum of BPSK/QPSK with trapezoidal waveform.

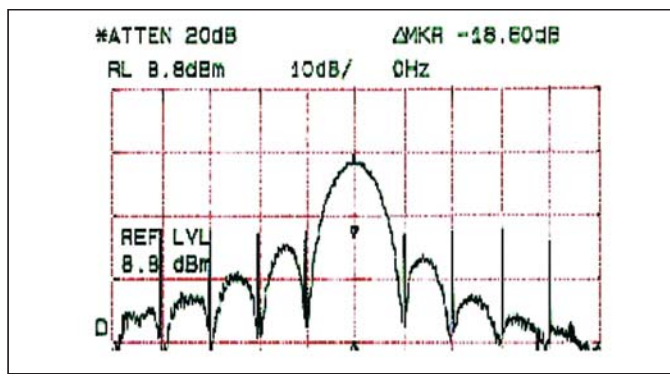


Figure 6 · Measured QPSK spectrum.

## Effects of High Bit Rate Data on QPSK Spectrum

When low bit rate data is modulating a carrier, the spectrum will be near ideal $(\sin x)/x$ profile similar to the one shown in Figure 1. But in practice, the spectrum will be far from ideal at high data rates. A typical RF spectrum measured on spectrum analyzer can be seen in Figure 6. Unwanted discrete line components can be seen in the observed spectrum. This is similar to the simulated spectrum shown in Figure 5. Asymmetry of the spectrum can also be noticed in the spectrum. Asymmetry increases with worsening rise and fall times.

## QPSK Modulator

A QPSK modulator designed and used onboard Indian Remote Sensing (IRS) Satellites is taken as an example for discussing the reasons for spectrum variations and their effects. The QPSK Modulator [1, 2, 3] at microwave frequencies has either a serial or a parallel configuration. The serial configuration consists of a 0°/90° and 0°/180° binary phase shifters connected in cascade. The more commonly used design is the parallel configuration shown in Figure 7. BPSK modulators which determine the performance of the QPSK modulator can be realized by using various techniques, and can be of transmission type or reflection type.

For IRS missions, reflection type BPSK modulators are used for realizing the QPSK modulator due to fabrication simplicity. A reflection modulator consists of either a circulator with one reflecting element or a hybrid with matched pair of reflecting elements. Switching diodes are most frequently used to achieve strong reflections in forward and reverse bias modes. PIN diodes are a better choice for reflection type modulators due to higher reflection coefficient, hence a lower modulation loss. A schematic of

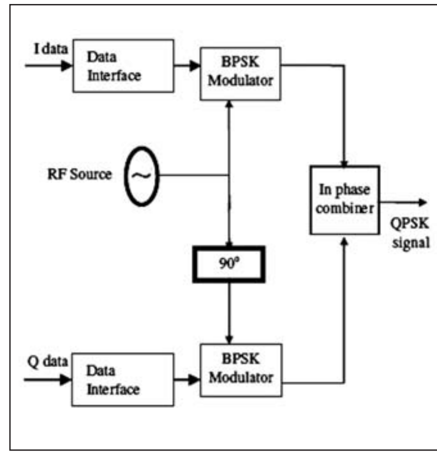


**Figure 7 · Block schematic of QPSK modulator.**

the reflection type modulator designed and used for Indian Remote Sensing satellites so far is shown in Figure 8. Switching quarter-wave transmission lines in the output branches of a quadrature hybrid helps to set the 180° phase accurately.

An interface circuit [3], shown in Figure 9 is used to reconstruct the data and synchronize the two data streams, as well as convert the levels for switching the diodes of the modulator. Poor rise/fall time has resulted in more data asymmetry after synchronizing and reconstructing the data streams with respect to clock, and causes considerable degradation in the RF performance. Degradation of the total link [4] due to bad rise/fall time and data asymmetry is shown in Figures 10 and 11.

### Carrier Leakage

The RF carrier component, along with components in the nulls of the spectrum, is often observed in high bit rate QPSK modulated signals as shown in the recorded spectrum in Figure 12. To provide a better explanation of the behavior of the data spectrum, simulations were carried out and the results are provided and discussed along with analysis for the observations made in the spectrum at different times. Presence of the carrier component can be due to either

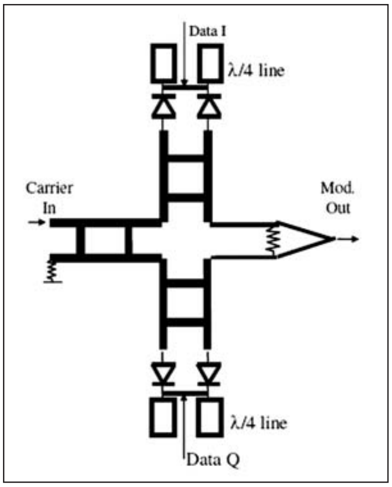


**Figure 8 · Schematic of a QPSK modulator.**

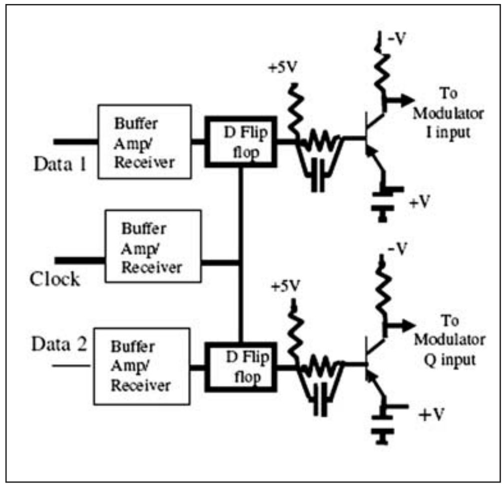


**Figure 9 · Data interface circuit of a reflection type QPSK modulator.**

poor carrier suppression in the BPSK modulator or higher DC content in the data streams.

Carrier suppression is an inherent quality of the modulator design and also depends on factors such as:

1. Switching speed of the devices used in the modulator circuitry

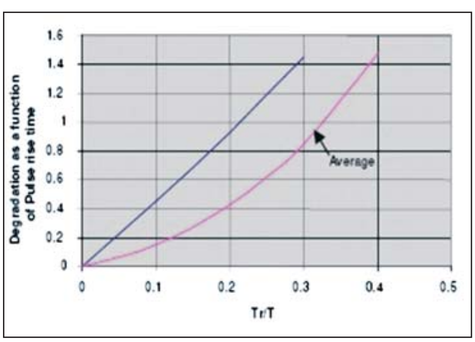


**Figure 10 · BER degradation with rise/fall times.**

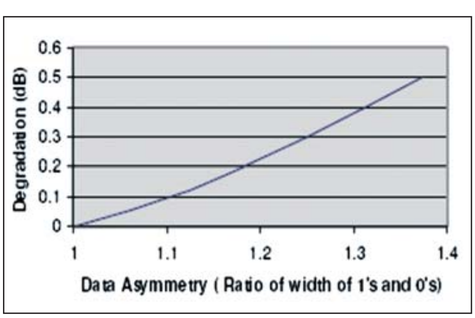


**Figure 11 · Degradation with data asymmetry.**

2. Rise time/fall time of the clock and data that is modulating the carrier
3. Duty cycle accuracy of the clock
4. Asymmetry of one and zero bits in the data streams

These parameters can increase the DC content in the modulating data stream which causes an increase of carrier leakage.

The carrier suppression is measured with 1010… type data. The typical QPSK spectrum modulated with 1010… data is shown in Figure 13. Ideally, the carrier components at centre frequency and between sidebands (at null points in the PRBS data modulated spectrum) shall be zero. But, practically, these components can not be avoided, although they can be minimized by good design, including good layout and packaging techniques.

Carrier leakage due to poor isolation of the hybrid coupler used for BPSK modulation is one of the main causes for the presence of carrier component in the output. Diode parasitic reactance also contributes to leakage of the carrier. Variation of carrier suppression is also noticed over operating temperature range due to the variation of parasitic reactance of the diodes with temperature. Practically, about 25 dB carrier suppression has been obtained in the modulators realized to handle 105 MBPS data for IRS missions. Moreover, data asymmetry causes the data to have average DC content which causes carrier to be present due to the DC content in the data.

Figure 14 shows spectrums observed by intentionally spoiling the data quality. The spectrum at top is with normal PRBS data for comparison while the spectrum at bottom is taken by intentionally spoiling the data by loading the data path in one of the data streams with the capacitance of oscilloscope probe. Carrier leakage increased considerably as expected, and the components at null points also increased. This observation confirms that the level of the components at nulls is related to carrier leakage. Thus, it is normal to have an increase in the level of the components at the nulls with increased carrier leakage.

Carrier leakage is sometimes observed to be more during payload data transmission, with the level varying. A typical data stream is simulated to have more “1” status bits. The spectrum is observed over some time, and the plots provided in Figure 15 were taken at different times with out changing any parameter. The lower figure shows more carrier leakage than the upper one. Because of continuous 1s at some places, the DC content in the stream will vary with time and the carrier leakage also seen varying with time, though data is not disturbed.

Figure 16 shows two spectrums plotted together for comparison, having PRBS data of (215 – 1) and (211 – 1) lengths. Carrier leakage is more for the spectrum in which the carrier is modulated with (215 – 1) PRBS data. These observations show that the spectrum effects and carrier leakage also depend on data.

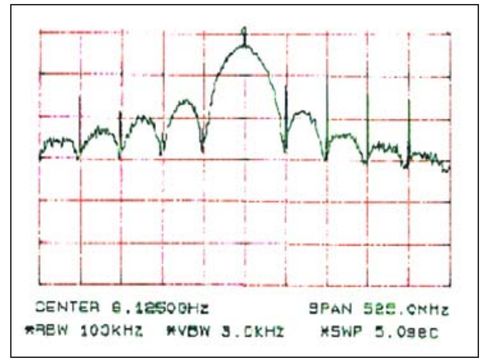


**Figure 12 · QPSK spectrum with noticeable carrier leakage.**

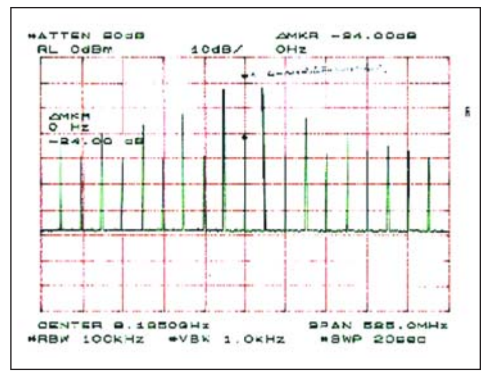


**Figure 13 · QPSK spectrum with 1010... data.**

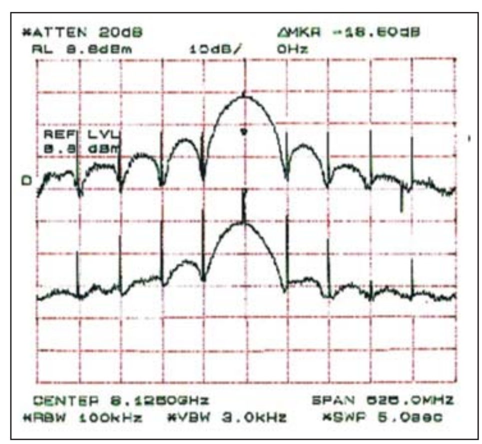


**Figure 14 · QPSK spectrum with distorted data.**

## Carrier Leakage at Higher Data Rates

Normally, about 90% of the power is available in the main lobe of the QPSK spectrum which occupies a bandwidth equal to data rate. When a lower data rate such as 50 Mbps is

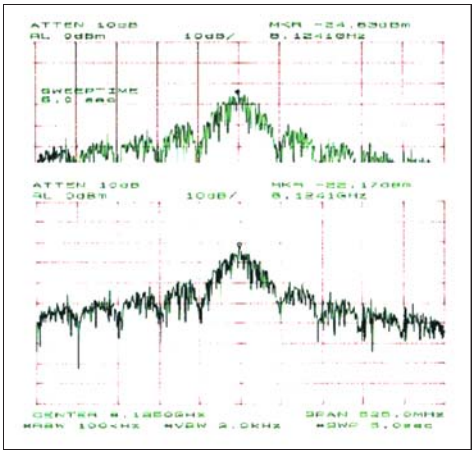

Figure 15 · QPSK spectrums observed over time.

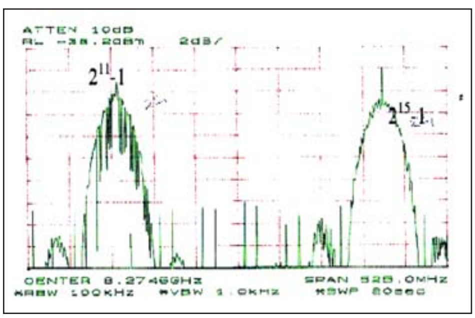


Figure 16 · QPSK spectrum with different PRBS data streams.

QPSK modulated, the transmitted power is distributed in a 50 MHz bandwidth with maximum power at the centre. When 100 Mbps data is modulated, same power will be distributed over 100 MHz bandwidth. The envelope will be down by 3 dB. At higher data rates, the carrier leakage will be greater in the modulator as explained earlier. Hence, with the same modulator having same carrier suppression characteristic, the carrier component is likely to be greater with higher bit rate data.

## Degradation Due to Carrier Leakage in the Link

The presence of components at carrier and in nulls of the side lobes in the QPSK modulated spectrum will result in wasted RF power. The power loss due to the increased level of the carrier leakage is calculated and given in Table 1. The transmitted spectrum is always filtered and discrete components in the first nulls are the only ones that contribute significantly to degradation in link performance. The level of the components seen in the first two nulls is assumed to be equal to the carrier component, which is the worst case that can be assumed. A QPSK modulated spectrum, having 6 dB increase in carrier leakage over normal practical spectrum is also assumed. As can be seen from the table, the power loss due to 24 dB normal carrier suppression is 0.5 dB and increases to 0.7 dB with 6 dB increase in carrier component. This degradation needs to be included in the link estimation.

The increase in the level of carrier leakage components can also be explained. The degradation due to this increase is about 0.2 dB with about 6 dB more degradation in carrier suppression and, as such, it is not of great concern with the increase in carrier leakage at times during the payload operation. Any carrier suppression more than 20 dB in a QPSK modulator can be tolerated by the system.

More severe is the degradation due to rise/fall times, data asymmetry and band limiting. Transmission modulators connect the input port to the output port via two switchable paths whose phase difference is 180°. A double balanced mixer, e.g. a ring quad of Schottky diodes, is a better choice for a transmission type BPSK modulator, as the data interface circuit will become simpler and degradation of rise/fall time and asymmetry of data will be less compared to PIN diode switched reflection type.

## Conclusion

To optimally use the limited bandwidth available for data transmission from space to earth, different parameters degrading the performance are addressed. Various parameters like rise time, fall time and asymmetry of the data pulses affect the spectral content. Carrier component and discrete components at null points in the spectrum are often randomly observed at high data rates. These were discussed and explained with simulation/observed results. Link estimation must take into account the degradation caused by these factors.

## Acknowledgements

Authors would like to place on record their appreciation for the encouragement given by Director, ISAC. They would also like to express their sincere thanks for the help and support extended by colleagues of Communication Systems Group, ISRO Satellite Centre.

## References

1. J.J. Spilker, *Digital Communications,* Prentice-Hall Inc., Englewood Cliffs, NJ, 1977.

2. Dr. Kamilo Feher, *Digital Communications Satellite/Earth Station Engineering*, Prentice-Hall Inc., Englewood Cliffs, NJ, 1981.

3. V. Sambasiva Rao et.al., "X-band High bit rate QPSK Modulator," *IETE Technical Review,* Vol 1, No. 4, pp 305-309, July-August 1993.

4. C. Louis Cuccia, "QPSK System Performance and impairments," *The Handbook of Digital Communications,* pp 87-93, vol. 9, Microwave System News, 1979.

| | | Normal carrier suppression | | Degraded carrier suppression | |
|---|---|---|---|---|---|
| Carrier suppression | | 24 | dB | 18 | dB |
| Total power | | 40 | watts | 40 | watts |
| Power in carrier + components in two nulls | | 0.48 | watts | 2.0 | watts |
| Useful power (90% in main lobe) | | 35.6 | watts | 34 | watts |
| Power loss | | -0.5 | dB | -0.7 | dB |
| | | | | | |
| Degradation | | | 0.2 | dB | |

**Table 1 · Degradation estimate due to carrier leakage.**

## Author Information

V. Sambasiva Rao is head of the Communication Systems Group at ISRO Satellite Centre. He is responsible for the development of high bit rate data transmitters for all IRS satellites and various RF and microwave systems for IRS and INSAT missions. He is a fellow of IETE and a member of Astronautical Society of India. He can be reached by e-mail at: vssrao@gmail.com

Dr. S. Pal is presently Distinguished Scientist & Deputy Director, and also Program Director, Satellite Navigation Program at ISRO Satellite Centre. He is responsible for the development and fabrication of all spacecraft related telecommunication systems for India's satellites. He is also on the United Nations panel of experts on Global Navigation Satellite Systems (GNSS).