MODULATOR IMBALANCE EFFECTS ON THE FQPSK AIRBORNE TELEMETRY LINK

Kip Temple
Air Force Flight Test Center

ABSTRACT

When designing transmitters for quadrature modulation schemes, the designer always tries to achieve good balance and symmetry of the in-phase (I) and quadrature (Q) branches of the modulator in terms of amplitude, phase, and offsets. Perfect balance between modulators is ideal but rarely if ever achieved. The Advance Range Telemetry (ARTM) program has placed indirect specifications on the remnant carrier and sideband levels which are controlled by modulator imbalance. These specifications will govern the ARTM programs first generation of Feher’s patented quadrature phase shift keying, version B (FQPSK-B) [9] airborne telemetry transmitters. The ARTM Program has also adopted test procedures for quantifying these modulation imbalances. This paper looks at the effects of modulator imbalances on spectral occupancy and bit error probability of the airborne telemetry link. It also outlines how these imbalances influence the levels in one of the ARTM specifications. Recommendations are presented based on the measured data for higher bit rate telemetry systems.

KEY WORDS

Transmitter, Quadrature modulator imbalance, Feher’s patented quadrature phase shift keying, Bit error probability

INTRODUCTION

Over the past several years, the Government telemetry community has been losing precious radio frequency (RF) spectrum to commercial interests. This coupled with increasing data rates has forced the Government to invest time and resources into finding more robust and bandwidth efficient means of transmitting test data. The Advanced Range Telemetry program was formed to examine and provide solutions to these problems. The first phase of the program was to find a more bandwidth efficient modulation scheme than the current standard, pulse-code modulation/frequency modulation (PCM/FM). The goal of the new scheme was to perform at least as well as PCM/FM in terms of bit error probability (BEP) and resynchronization time and be compatible with nonlinear amplification. Also, any new
ground-station equipment had to be compatible with existing-ground station configurations. The chosen modulation scheme was Feher’s patented quadrature phase shift keying, version B, revision A1 or FQPSK-B, rev A1[9].

With this new modulation scheme came a new set of issues the telemetry community didn’t have to worry about when using PCM/FM. A new type of modulator was required to construct FQPSK from a baseband Non-Return-to-Zero, Level (NRZ-L) signal. This modulator, a quadrature modulator, has inherent sources of errors such as phase noise and imbalances between the in-phase and quadrature channels.

Imbalances in quadrature modulators can cause spurious tones and spectral spreading in the modulated spectrum, distorted signal constellations, degraded demodulator performance, and slight degradations in the BEP performance of the telemetry system.

**I/Q IMBALANCE**

In order to understand what is meant by quadrature modulator imbalances, a model of a perfect IQ modulator is shown in Figure 1.

![Figure 1 – Basic Quadrature Modulator](image)

The output signal, \( S(t) \) of the perfect modulator can be expressed as the sum of the I and Q-channels as shown in Equation 1-1:

\[
S(t) = S_I(t) \cos(2\pi f_0 t) + S_Q(t) \sin(2\pi f_0 t) \tag{1-1}
\]

where \( S_I(t) \) is the I-channel information signal, \( S_Q(t) \) is the Q-channel information signal and \( f_0 \) is the local oscillator (LO) frequency or in more familiar terms the carrier frequency.

Since perfectly balanced modulators are hard to come by, the sources of modulator imbalances must be determined. Dominant first order error sources come from the in-phase, I-channel and the quadrature, Q-channel being out of balance in amplitude and in quadrature (90-degree separation of I and Q-channels). Direct current (DC) offsets can also occur on the I-channel, Q-channel or both. The following four terms will be used when discussing quadrature modulator imbalances:
1. Quadrature Error – Amount of phase error from perfect quadrature between the I and Q vectors.
2. I Offset – Amount of origin offset or DC offset on the I-channel.
3. Q Offset – Amount of origin offset or DC offset on the Q-channel.
4. I/Q Gain Imbalance – Amount of relative amplitude imbalance between the I and Q channel.

A model of a generic FQPSK modulator with imbalances is shown in Figure 2. The diagram illustrates how a FQPSK modulator might be realized and where imbalances will occur.

\[
S(t) = [S_I(t) + A_I] \cos(2\pi f_c t) + G[S_Q(t) + A_Q] \sin(2\pi f_c t + \Delta \theta) \tag{1-2}
\]

From the equation, four new terms have been added from the previous equation. \(A_I\) and \(A_Q\) are DC bias terms for the I and Q-channels which is the same as I offset and Q offset from above. \(G\) is the I/Q gain imbalance term and \(\Delta \theta\) is the quadrature error term.

To get an intuitive feel for the effects of modulator imbalances, think in terms of the vector diagram or a sampled vector diagram otherwise known as a constellation diagram [7] (Figure 3).
results in equal lengths of I and Q and the I and Q axes are 90-degrees apart. A quadrature error would cause the unit circle to become an ellipse (I and Q axes not 90-degrees) and a phase rotation of the detection points in a constellation diagram. Amplitude imbalance would cause the I and Q values to be of different length which also causes the circle to become an ellipse. A DC offset (origin offset) would cause the vector to start from some other location than the origin [3]. All of these imbalances cause the detection points to move away from their optimum locations causing errors in bit detection at the receiver.

ARTM TESTS

The ARTM program will test fully functional prototype airborne transmitters with no access to the internal I/Q modulator circuitry. Because of this, external test methods were adapted to verify proper operation and interoperability of the transmitter. Two tests play a key role in determining acceptable levels of modulator signal quality, the power spectral density mask as defined by Inter-Range Instrumentation Group (IRIG) document 106-00 [8] and the Single Sideband (SSB) test [5]. Transmitters with significant modulator imbalances will produce a spectrum that is a violation of the spectral mask. The SSB test also gives an indication of modulator imbalances. A known bit pattern is sent to the modulator that after the differential encoder produces 180-degree phase shift on a symbol to symbol basis. This bit pattern applied to the baseband input causes an ideal FQPSK-B transmitter to produce a full power sideband tone offset from the carrier frequency by precisely Rb/4 where Rb is the bit rate (hence the name single sideband). A perfectly balanced transmitter will have only a component at the carrier frequency offset by Rb/4. As can be seen in the first plot in Figure 4, this is not the case for an imperfect modulator. Not only is the sideband present, but also the carrier and the opposite sideband (referred to as the image throughout the remainder of the paper). Relative amplitudes of the carrier, sideband and sideband image give an indication of the I/Q modulator balance. An example output of an FQPSK transmitter response to the SSB test and the modulated waveform with the spectral mask is shown in Figure 4. Bit rate for this example was 14.7Mbps.

![SSB Test Results](image1)

![Spectral Mask](image2)

Figure 4 – SSB Test and FQPSK Spectrum
The test setup as shown in Figure 5 consists of a way to modulate and demodulate FQPSK either at an intermediate frequency (IF) of 70MHz or RF of 1450MHz. For this test, \( f_0 = 1450 \text{MHz} \) was selected. The combination of the laptop, I/Q modulation generator, external filter, signal generator and low power class C amplifier defines the ARTM reference transmitter. There are an unlimited amount of bit rates that can be programmed into the reference transmitter but for this test, 14.7Mbps was selected. The laptop controls the I/Q modulation generator that allows the user to select the baseband signal file to be modulated. There are various choices, but two files were used throughout the testing. First was the sequence of all 1’s to generate the spectrum for the SSB Test. Second was a 11-bit pseudo random bit
sequence (PRBS) per the IRIG standard [8] that was used for bit error rate testing. After modulation and amplification, the reference transmitter’s signal is translated to 70MHz and sent through the noise and interference test set. This allowed direct control of $E_b/N_0$ values. The RF Networks demodulator was used as the reference demodulator and the bit error rate analyzer provided BER statistics. Peak hold was used on the spectrum analyzer with settings; RBW= 10kHz and VBW=1kHz.

The Hewlett-Packard E4432B Signal Generator allows the user to introduce and control four modulator imbalance terms. The four adjustable parameters are I/Q gain imbalance, I offset, Q offset and quadrature error. These adjustments were used to vary the carrier suppression and image level during the SSB test. When the levels were adjusted to achieve the desired carrier suppression and image levels, the PRBS file was loaded to create a modulated spectrum. This was then demodulated and using the noise and interference test set, BEP curves were developed.

**TEST RESULTS**

Is the telemetry link affected by transmitter modulator imbalances? How much imbalance can cause degradations? To answer these questions, imbalances must be introduced in a controlled manner. Using these imbalances, BEP tests and spectral plots must be made to quantify the degradations. These imbalances were recorded, BEP tests were performed, and spectral plots were made to show the effects on the modulated spectrum.

One method to test link performance is to transmit a known bit pattern, detect it and check for any errors. This is commonly referred to as a Bit Error Probability test or BEP. Figure 6 is a plot of four BEP measurements taken with varying levels of carrier suppression and image level. The curve labeled ‘Reference’ was derived by maximizing carrier suppression (CS) and minimizing image level (IL) using the SSB test by optimizing the modulator imbalance parameters. At these settings, carrier suppression was 66dBc and image level was –69dBc. Throughout all of the testing, this modulator setting was used as the baseline for the SSB, spectrum and BEP tests. The second curve was based on the allowable minimum value of carrier suppression (25dBc) and maximum image level (-30dBc) currently in the ARTM specifications. The third curve was based upon an intermediate value of carrier suppression and image level between the ‘Reference’ and current ARTM specifications. The fourth curve is the four-point BEP limit called out in the ARTM specification.

Notice how the second curve with the ARTM specified limits of carrier suppression and image level falls on top of the fourth BEP curve. This shows consistency and correlation between two of the ARTM specifications defining transmitter quality.
IQ Balance Effects
14.7Mbps, 1450MHz, NLA

Eb/No (dB)

BEP

Reference
CS 25dBc, IL -30dBc
CS 40dBc, IL -35dBc
ARTM BEP Spec

Figure 6 – Bit Error Probability Curve

Spectral plots were then done for these settings of modulator imbalances. Figure 7 is a spectral plot of the system utilizing the ‘Reference’ modulator settings. Of particular interest is the spectral plot of the modulated FQPSK waveform, Figure 8, with the carrier suppression and image level set to the current ARTM specification.

Figure 7 – 14.7Mbps Reference Spectrum
To arrive at these levels of carrier suppression and image level, I offset was –7.5 percent (–37.5mV), Q offset was 7.5 percent (37.5mV), quadrature skew was –5-degrees, and I/Q gain was –1.2dB. Notice the spurious tones spaced at \( n \) integer multiples of the symbol rate. The spectrum violated the spectral mask as defined in IRIG 106-00 [8] at these points which for this case are offset from the carrier \( n=1 \) (±7.35Mhz) and \( n=2 \) (±14.7MHz). The mask was also violated by the modulated spectrum in the range of –60dBc to –70dBc.

For higher bit rate transmitters, the ARTM specification of 25dBc carrier suppression and –30dBc image level may not be sufficient. For this bit rate, a carrier suppression level of 40dBc was required so no significant spurious tones were present in the modulated spectrum. Granted, this is a very high level of carrier suppression, but if negligible spurious tones are a requirement, 40dBc of carrier suppression was required. Levels higher than this created very noticeable spurious tones using the specified spectrum analyzer settings. An image level of –35dBc was required to keep the spectral spreading within the spectral mask. Image levels higher than this caused spectral spreading which exceeded the spectral mask. Refer to Figure 9 and 10 for the modulated spectrum and SSB test results for these levels of carrier suppression and image level. Figure 6 shows the BEP of the system with these levels. As can be seen, there is little difference in BEP performance between the ‘Reference’ curve and the curve using these levels.
Tests were also conducted to explore interactions of the imbalance parameters and the ARTM defined modulator quality specifications for carrier suppression and image level. Tests were performed to determine which imbalance parameters affected carrier suppression and image level. Next was to verify the level of interaction, and then finally to what level these interactions were decoupled from each other. It was found that within certain ranges, I and Q offset affected carrier suppression and I/Q gain and
quadrature skew affected image level. Also, carrier suppression and image level were largely decoupled. That is, if I and Q offset was varied to achieve a certain level of carrier suppression, then the image level would not vary. This was also true for I/Q gain and quadrature skew to adjust image level, carrier suppression was not affected. These imbalance numbers were plotted and presented to demonstrate these interactions and how small imbalances have a large impact on the parameters of carrier suppression and image level which affect the telemetry link in general.

Figure 11 is a plot of I and Q DC offset versus carrier suppression. For the Hewlett-Packard signal generator, full-scale offset was 500mV. For a ±1-percent change in offset, or in terms of voltage, ±5mV, carrier suppression went from a minimum of ~70dBc to ~45dBc. Control of 5mV of DC offset when circuit designing is not a trivial task and in this case very important.
Figure 12 shows a plot of quadrature skew versus image level. Again, notice the narrow window of optimum performance. Within $\pm 1$-degree adjustment of quadrature skew the image level can vary between 20-25dB from a minimum of -69dBc to -46dBc.

Fig. 12 – Quadrature Skew versus Image Level
I/Q gain imbalance is plotted as a function of image level in Figure 13. A value of +1dB of gain imbalance means the I-channel will have 1dB more amplitude than the Q-channel. A value of –1dB means the I-channel will have 1dB less amplitude than the Q-channel. Referring to the plot, small fluctuations of I/Q gain cause large level changes in the image. Just 0.1dB of gain imbalance caused 20-25dB of image level change.

Figure 13 – I/Q Gain versus Image Level

Notice the very narrow window of optimum performance for all four imbalance parameters. Building a good I/Q modulator truly is a balancing act. Within a certain range of values close to the optimum modulator balance point, carrier suppression controlled the level of the spurious signals in the modulated spectrum as seen in Figure 8. Less carrier suppression caused greater level of spurious signals. Carrier suppression can be controlled to a great extent by varying I and Q offset. Within this same range of values, image level controlled the amount of spectral spreading. A greater level of image signal caused more spectral spreading. Comparing Figures 7 and 8 at the –60dBc points demonstrate this spreading. Image level can be controlled to a great extent by varying I/Q gain and quadrature skew.

As the levels of imbalance get farther and farther away the optimum operating point, I and Q offset starts to affect carrier suppression and quadrature skew and I/Q gain start to affect image level. This in turn causes interaction between carrier suppression and spectral spreading as well as interaction between image level and spurious tone level.
CONCLUSION

Modulator imbalances do effect the performance of an FQPSK telemetry link. The BEP performance and the modulated spectrum are adversely affected with greater levels of I & Q offset, I/Q gain, and quadrature skew. As was shown, the spectrum suffers the most with greater modulator imbalances.

Serious quadrature modulator imbalances, outside of the limits presented here, do not greatly affect the BEP performance of the demodulator, generally not more that 0.5dB. This was demonstrated by comparing what was deemed the reference system with a system generating FQPSK with a grossly imbalanced modulator.

With real-world quadrature modulators, large modulator imbalances result in spurious signals at frequency offsets equal to integer multiples of the symbol rate. Greater imbalances caused less amount of carrier suppression, larger image level (in the SSB Test) and larger levels of spurious tones.

Within the range of ±20mV, I and Q offset directly controls the amount of carrier suppression which also directly controls the level of the spurious tones in the modulated spectrum. Larger I and Q offsets caused a smaller amount of carrier suppression and thus larger tones. Within a certain range, I/Q gain (+0.4dB) and quadrature skew (+3.5-degrees) directly controlled the image level. Lower image levels caused less spectral spreading of the modulated waveform usually in the range of –60dBc to –70dBc. Higher image levels caused more spectral spreading. Above these limits, I and Q offset, I/Q gain, and quadrature skew all contribute to spectral spreading. Within these given ranges of imbalances, the affects of were largely decoupled from each other. I and Q offset did not affect the image level, quadrature skew and I/Q gain did not affect carrier suppression.

The simple first order modulator model presented does not accurately represent all of the interactions inside of a realizable IQ modulator. Second, third, and fourth order interactions within each component and between components were beyond the scope of this paper.

The ARTM specifications for carrier suppression of 25dBc and image level of –30dBc for the SSB Test maybe adequate for 1-2Mbps transmitters. But as the bit rate increases, higher carrier suppression and lower image levels will be required in order to meet the spectral mask requirement.

Imbalance figures were presented to give some insight into how modulator imbalances affect the quadrature modulator. These numbers are not meant as hard and fast rules but to give a feel for design constraints for an IQ modulator. Different modulator designs and variations from modulator to modulator will exist so these numbers may not directly apply to other designs.
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REFERENCES


9. FQPSK is an acronym for “Feher’s Quadrature Phase Shift Keying”, a proprietary variation of offset quadrature phase shift keying controlled by DIGCOM Incorporated, El Macero, CA.