Organizations such as the National Telecommunications and Information Administration (NTIA), Federal Communications Commission (FCC), International Telecommunications Union (ITU) and various commercial entities use a wide range of spectral efficiency criteria in different broadcast and wireless system applications. These criteria and related specifications have significant differences. This paper briefly reviews some common adjacent channel interference (ACI) definitions as well as issues surrounding the definition of spectral efficiency. The impact of these parameters on system bit error rate (BER) performance and closely "packed" adjacent signals is described. ACI criteria and spectral efficiency definitions considered appropriate for existing telemetry applications and deployment of new generations of spectrally efficient systems are illustrated. Specific ACI and spectral efficiency performance requirements adopted by the Department of Defense (DoD) and Advanced Range Telemetry (ARTM) project are highlighted.

KEY WORDS
adjacent channel interference (ACI), spectral efficiency, Feher patented Quadrature Phase Shift Keying (FQPSK)

INTRODUCTION
With the continual increase in demands for higher bit rate digital wireless, cellular, personal communications services (PCS), telemetry and broadcasting applications, frequency bands are becoming crowded and frequency spectrum scarce. The need for
improved spectral efficiency leads to deployment of more efficient systems having lower out-of-band ACI while maintaining robust bit error probability (BEP) performance. In the class of power efficient systems compatible with non-linear amplification (NLA), non-return-to-zero (NRZ) pulse code modulation/frequency modulation (PCM/FM) and Feher patented quadrature phase shift keying (FQPSK) are used as illustrations in this paper.

Among the most important issues are: (1) spectral containment, and (2) performance in the presence of noise and interference. The parameter satisfying the spectral containment criterion is spectral efficiency and, for performance comparison, BEP is the basic metric. The two typically complement one another, as it is impossible to effectively optimize one parameter independently of the other.

POWER SPECTRAL DENSITY AND ADJACENT CHANNEL INTERFERENCE

Power spectral density (PSD) of a modulated signal and its ACI are closely related. PSD measures power in the signal normalized to a 1 Hz bandwidth (BW) at a given frequency offset, while ACI provides a measure of spectral power of the modulated RF signal spectrum spilling over into adjacent channels. ACI interpretation and impact depends on the application, and for this reason many definitions exist. In this paper the definitions under review are: (1) the brick-wall filter per North American Digital Cellular Standard, Interim Standard-54 (IS-54); (2) integrated out-of-band power ACI (3) ACI under a specific bandpass receive filter and (4) total signal power relative to power in adjacent interferer(s). ACI meaning and interpretation is now discussed.

Adjacent channel interference is computed by knowing: (1) the power spectral density of the transmitted signal S(f); (2) the normalized 3 dB bandwidth of the bandpass receive filter at the intermediate frequency (IF) denoted by BiTb (not to be confused with the BTb bandwidth-bit duration product in the transmit baseband filters); (3) the bandpass receive filter frequency response; (4) the receive detection filter frequency response, (5) and the normalized channel spacing W. The parameters BiTb and W are normalized to the bit rate. The next three sections highlight differences between the ACI definitions used in several commercial applications and standards.

ACI: IS-54 Definition

The IS-54 ACI model sprouts from the requirement that the first adjacent channel power must be attenuated by 26 dB below the carrier power in a brick-wall channel spacing of 30 kHz. For this model the receiver is assumed to have a brick-wall bandpass filter with bandwidth equal to the channel spacing, thus BiTb=W. Figure 1 illustrates the complex baseband representation of the transmitter's modulated signal of a single channel with channel spacing W. Also shown are two brick-wall bandpass receive filters. The filter on the left corresponds to a receiver in the same channel as the transmitter, and the filter on the right corresponds to a second receiver that occupies the right adjacent channel. If the
right adjacent channel receiver has its bandpass filter centered around W with channel spacing W, then the sideband of the spectrum of Figure 1 would interfere with this receiver's ability to demodulate its transmitter signal (not shown). In other words the region (2) of Figure 1 represents the amount of spectral leakage, i.e. integrated ACI, into the adjacent channel receiver with a bandpass filter centered around W Hertz and a bandwidth of W Hertz.

The amount of interfering integrated power relative to the main channel integrated power as a function of channel spacing is specified. In this case the interfering power is the integrated power spectral density over a bandwidth equivalent to the channel spacing W. The IS-54 ACI model provides a metric for estimating Signal-to-Interference ratio in a frequency multiplexed system based on the transmitter spectral performance only, as no receive filter assumptions are made.

ACI: Out of Band Power Definition
This second definition for ACI is known as percent out-of-band power. Figure 2 illustrates the out of band power definition. It gives an indication of the ratio of the total amount of integrated power density that is outside the main channel power relative to the main channel power. The interfering energy is not only limited to the first adjacent and second adjacent, but to all the modulation induced interfering spectra outside the main channel and can be expressed in terms of relative percentage or in decibels.
ACI with Specific Receive Filter
The third definition for adjacent channel interference involves the specification of the receive IF bandpass filter or channel shaping filter. This filter is typically located after the wideband roofing bandpass filter in the IF down conversion path of a receiver. Practically speaking, the channel shaping filter is not the same as the pulse shaping filter found in the demodulator and before the detection process. In calculating the ACI the magnitude response of the bandpass receive filter \(|H(f)|\) must be known. Again, knowing the power spectral density \(S(f)\), the ACI can be computed using the following equation,

\[
ACI_{RX-filt}(W) = \int_{-\infty}^{\infty} S(f) |H(f-W)|^2 df \Bigg/ \int_{-\infty}^{\infty} S(f) |H(f)|^2 df
\]  

(eq. 1)

This model incorporates a bandpass receive filter and provides estimates that are closest to practical systems. Unlike the IS-54 ACI model which provides more conservative (higher) ACI estimates, the specific receive filter model is primarily used.

Figure 3A shows the frequency spectra of three identical modulation formats under a frequency division multiple access scheme with the middle spectrum assigned as the desired channel. The bandpass receive filter (arbitrarily shown as a brick-wall) is centered in the desired channel and collects power both from the desired transmitting station and two additional stations broadcasting in the adjacent channels. In a practical environment the receive powers from the transmitting stations are not equal due to near/far propagation effects. However, they are shown as such for illustrative purposes.
The bandpass filter output in the receiver perceives the power of the desired transmission (shown in Figure 3A as shaded region [1] and the undesired or interfering power from both adjacent channels (shaded region [2]). The ratio of the two areas, shaded area [2] to shaded area [1], is the ACI for the channel spacing. Figure 3B illustrates the computation concept.

Figure 3A: Illustration of Adjacent Channel Interference with a specific receive filter. The receive bandpass filter is arbitrarily drawn as a brick-wall filter. The points at which the spectra intersect with the frequency axis is zero Watt/Hz.

Figure 3B: Illustration of ACI computation with arbitrary receive filter.
Once $S(f)$ is known, integrated ACI is easily calculated for signals that are downconverted, coherently demodulated and detected at baseband. Figure 4 shows the calculated ACI for FQPSK-B$^{2,3}$. These values were calculated using the spectrum presented in Figure 5. The signal is assumed to pass through a bandpass filter (BPF) with -3 dB bandwidth equal to the bit rate and shape typical of receiver IF filters currently used at test ranges and a 4-pole lowpass filter (LPF) having characteristics designed for near optimum detection of the modulating signal. Different ACI results will be attained with different assumptions.

![Figure 4. Integrated ACI for FQPSK-B (BPF plus LPF).](image)

**ACI: Total Signal Power Relative to Interference Power**
Yet another ACI metric is preferred for telemetry applications because it directly accommodates unequal power relationships, adapts to tests with mixed modulation types and directly relates to laboratory test configurations. One measures the ratio of total power in the desired signal to total power in the interfering signal (C/I). System BEP performance is then measured while varying the C/I ratio and W.

**ACI Effects ON BEP: A Telemetry Example**
ACI measurements$^3$ were performed by summing a second non-linearly amplified signal (with attenuator after power amplifier) with the desired signal. Experiments were conducted as follows:

1. Disconnect second signal, find attenuator setting which gives BEP of $1 \times 10^{-5}$, decrease attenuation by 1 dB.
2. Connect second signal, set frequency offset equal to bit rate, vary attenuator on second signal until BEP is again $1 \times 10^{-5}$. Measure relative levels of the two signals at the output of the summing amplifier.
3. Increase frequency of second signal by 0.1 bit rate and repeat step 2.
Sample results are listed in Table 1. These results show that a 1 Mb/s NRZ PCM/FM had a 1 dB degradation with a 1 Mb/s NRZ PCM/FM interfering signal 23 to 25 dB larger than the desired signal with a frequency spacing of 2 MHz and an IF bandwidth of 1 MHz.

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Frequency Separation (MHz)</th>
<th>IF BW (MHz)</th>
<th>C/I (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRZ PCM/FM</td>
<td>1.0</td>
<td>1.0</td>
<td>10</td>
</tr>
<tr>
<td>NRZ PCM/FM</td>
<td>2.0</td>
<td>1.0</td>
<td>-23 to –25</td>
</tr>
<tr>
<td>NRZ PCM/FM</td>
<td>2.4</td>
<td>1.0</td>
<td>-40</td>
</tr>
<tr>
<td>NRZ PCM/FM</td>
<td>2.4</td>
<td>1.5</td>
<td>-24</td>
</tr>
</tbody>
</table>

Choosing an appropriate ACI metric is just half of the job. Before system level specifications, operation plans and system maintenance requirements can be developed, sensitivity of the receiving system to ACI must be known. Even though simulation technology is quite advanced today, simulated ACI sensitivity is best used to discern major differences between candidate systems. Reliable ACI performance information still requires tests on real hardware.

**SPECTRAL EFFICIENCY DEFINITIONS IN TELEMETRY**

Spectral efficiency in digital modulation systems is most commonly described with the ratio of the number of bits per second that are transmitted per Hz of bandwidth. This convention is appropriate for general telemetry applications. While useful, this ratio, with units of bits/second/Hz (b/s/Hz), can be very misleading. Spectral efficiency citations are not valid unless accompanied by clear statements of bandwidth criteria used for the calculations. Since out of band (adjacent channel) PSD attenuation versus frequency offset from carrier varies dramatically among different digital modulation families, meaningful spectral efficiency figures are based on bandwidth criteria consistent with the application. For example, it is far more costly to lose segments of digital data transmission from a multi-million dollar missile test flight due to ACI than it is to lose a few verbal utterances during a digital telephone conversation. Thus, spectral efficiency bandwidth should be chosen for consistency with ACI criteria which in turn establishes the “necessary bandwidth” used by regulatory agencies.

PSD of the NLA signal is by itself an important transmitter specification. Operational ACI criteria for the DoD standard NRZ PCM/FM signals preferred in DoD test range applications are well established and are normally consistent with setting necessary bandwidth at approximately 60 dB below the unmodulated carrier (dBc). Equation 2 is an
empirical equation for the −60 dBc bandwidth required of Range Commander’s Council standard random NRZ PCM/FM signals:

\[ B_{-60\text{dBc,FM}} = b \left( 2.78 - 0.3 \log b \right) \]  

(eq. 2)

where \( B \) is in MHz and \( b \) is bit rate in MHz. The ARTM project has established a preliminary quality control spectral mask for FQPSK-B modulation:

\[ M(f) = -63 + 90 \log b - 100 \log |f - f_c| \]  

(eq. 3)

where \( M \) is the mask limit in dBc, \( f \) is frequency in MHz and \( f_c \) is carrier frequency in MHz. The spectrum of a 10 Mb/s FQPSK-B signal is illustrated in Figure 5 and that of a 10 Mb/s NRZ PCM/FM signal in Figure 6. The important spectrum analyzer settings were: resolution BW=10 kHz; video BW=1 kHz, and max hold detector. Numerical values of these spectra associated with different bandwidth definitions are illustrated in Table 2. Corresponding spectral efficiencies are listed in Table 3. The spectral masks of FQPSK-B and of NRZ PCM/FM are also shown in Figures 5 and 6.

![Figure 5. FQPSK-B spectrum and spectral mask (10 Mb/s).](image)

![Figure 6. NRZ PCM/FM spectrum and spectral mask (10 Mb/s).](image)

<table>
<thead>
<tr>
<th>Bandwidth Criterion</th>
<th>NRZ PCM/FM (MHz)</th>
<th>FQPSK-B (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>99%</td>
<td>11.6</td>
<td>7.8</td>
</tr>
<tr>
<td>99.9%</td>
<td>19.8</td>
<td>9.8</td>
</tr>
<tr>
<td>99.99%</td>
<td>24.0</td>
<td>12.6</td>
</tr>
<tr>
<td>-60 dBc</td>
<td>25.2</td>
<td>12.9</td>
</tr>
<tr>
<td>-65 dBc</td>
<td>26.6</td>
<td>15.2</td>
</tr>
<tr>
<td>Bandwidth Criterion</td>
<td>NRZ PCM/FM (b/s/Hz)</td>
<td>FQPSK-B (b/s/Hz)</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>99%</td>
<td>0.86</td>
<td>1.28</td>
</tr>
<tr>
<td>99.9%</td>
<td>0.51</td>
<td>1.02</td>
</tr>
<tr>
<td>99.99%</td>
<td>0.42</td>
<td>0.79</td>
</tr>
<tr>
<td>-60 dBC</td>
<td>0.40</td>
<td>0.78</td>
</tr>
<tr>
<td>-65 dBC</td>
<td>0.38</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Table 3 lists spectral efficiency values of 0.4 and 0.78 b/s/Hz for NRZ PCM/FM and FQPSK-B respectively at -60 dBC bandwidth and b=10 Mb/s. If 99% power bandwidth is used (a common basis in regulatory references and some commercial applications) the respective spectral efficiency’s are 0.86 for NRZ PCM/FM versus 1.28 for FQPSK-B. Again, the choice should be based on ACI. Assume equal bit rate channels of 10 Mb/s signaling. Spectral efficiency based on 99% bandwidth implies one could pack eight NRZ PCM/FM channels or twelve FQPSK-B channels into a 100 MHz frequency band. However, if you want individual channels to operate successfully in DoD range applications, the ACI based spectral efficiency numbers yield a choice of four NRZ PCM/FM channels or seven FQPSK-B channels.

**ILLUSTRATIVE SPECIFICATIONS – ARTM EXAMPLE**

Spectral efficiency (with an appropriate bandwidth definition) was used to select candidate modulation methods for analysis and testing. FQPSK-B modulation is proposed as the best method for a next generation upgrade to telemetry systems. From this point, the spectral mask (equation 3) will be used to specify spectral efficiency and transmitter ACI indirectly.

ARTM specifications\(^6,7\) for FQPSK-B transmitters and demodulators take a direct heuristic approach to ACI control by limiting allowable degradation of BEP performance. Table 4 lists the current baseline BEP versus energy per bit to noise density ratio (\(E_b/N_0\)) performance limits with additive white Gaussian noise (AWGN). The limits are derived from laboratory and field trials of real 1 Mb/s and 5 Mb/s FQPSK-B equipment and are well above theoretical limits derived from simulations. They also reflect inclusion of differential encoding and exclusion of error detection (channel) coding in the system design.
Table 4. FQPSK-B AWGN BEP Performance Limits

<table>
<thead>
<tr>
<th>BEP</th>
<th>Maximum $E_b/N_0$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-4}$</td>
<td>10.0</td>
</tr>
<tr>
<td>$10^{-4}$</td>
<td>12.0</td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td>13.5</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>15.0</td>
</tr>
</tbody>
</table>

The full burden of received ACI control is placed on the demodulator, i.e., no assistance from upstream bandpass filters is assumed. Allowable ACI degradation is specified in terms of a specific test. Two FQPSK-B signals operating at the same bit rate are spaced at $W = 1.2$ times the bit rate. Interfering signal power is 20 dB higher than the desired signal. The value of $E_b/N_0$ required to produce a BEP of $10^{-5}$ or better is allowed to increase as much as 1 dB.

The 20 dB power differential is a negotiated figure selected to accommodate near-far signal power relations known to occur in DoD test range applications. $W$ is a conservative value in terms of hardware design potential, but is consistent with ACI capability found in tests of practical FQPSK-B equipment to date.

**CONCLUSIONS**

This paper briefly reviewed several common ACI definitions and noted current preferences for telemetry work. Introduction of spectrally efficient modulation methods to DoD telemetry applications means that for a time, ACI related to new methods must be dealt with in terms of mixed modulation modes, unequal power levels and arbitrary bit rates. This seriously complicates ACI issues. Additional work is needed to document system ACI sensitivity and establish optimum values of $W$ for operations and system designs as a function of modulation type, relative power levels and receiver design.

**REFERENCES**

2. K. Feher et al.: U.S. Patents 4,567,602; 4,644,565; 5,491,457; 4,339,724; 5,784,402, post-patent improvements and other U.S. and international patents pending. For Feher patented FQPSK and GMSK licensing and technology transfer information, contact: FQPSK Consortium-Digcom, Inc., c/o Dr. K. Feher; 44685 Country Club Dr.; El Macero, CA 95618; Tel. 530-753-0738; Fax 530-753-1788; E-mail feherk@yahoo.com


