Power Measurements on Digitally Modulated Signals

Introduction

The most basic definition of power describes it as the rate at which work is performed or energy is transferred. It seems like such a simple concept, yet power measurements are anything but simple. In communications even the definition of power takes on many forms: peak power, average power and adjacent channel power, for example. These terms all describe power measurements which give an indication of some unique aspect of system performance.

Even for a given type of power measurement there can be many variations. When we talk about the average power of a TDMA signal, are we referring to the average power while the carrier is on, or the average power over all time? Although there are many different types of power measurements, they can all be placed in one of three categories: time selective, frequency selective, or time and frequency selective. In this paper we analyze measurements that fall into each of these three categories and determine what type of instrumentation is required to make each measurement. We also describe the advantages and limitations of using different types of equipment for specific measurements. Before we can do that, however, we need to understand the characteristics of the signal to be measured. So, we'll start with a review of the basic time and frequency domain relationships of several different signals.

Time, Frequency and the Fourier Transform

Just as there are right and left-handed people, so too are there people who mostly think about signals in the time domain, and people who mostly think about signals in the frequency domain. And just as there are a few people who can comfortably use either hand, there are also a few people who can shift easily between thinking about a signal and its spectrum. For time and frequency selective power measurements it's important to understand the general signal characteristics in both domains, since without this understanding, data can be misinterpreted, or worse yet, the instrumentation improperly configured. Even if you're not *ambidextrous* you can easily predict a signal's characteristics if you know a few basic Fourier transform pairs and identities.

Fourier Transform

$$X(f)=\int_{-\infty}^{\infty} x(t)\cdot e^{-j\cdot 2\cdot\pi\cdot f\cdot t}\,dt$$

Inverse Fourier Transform

$$x(t)=\int_{-\infty}^{\infty} X(f)\cdot e^{j\cdot 2\cdot\pi\cdot f\cdot t}\,df$$

The Fourier transform is such a fundamental tool to electrical engineers that they often forget some of the basic assumptions that go along with it. For example, who can say that they've actually observed a signal over a time period extending from minus infinity to infinity? No one has. Instead, most of us compromise by looking at a signal over shorter periods of time and then assume that our observations are close to what we'd get if we had observed the signal over all time. Alternatively, we assume that the signal is periodic and that we only need to measure over one period of the signal to understand what the signal is doing at all other times. A variation on this second assumption is the assumption that the signal is stationary and that it doesn't matter at which point or points in time the signal is observed. For example, swept spectrum analysis uses this assumption since each frequency point is measured at a different time.

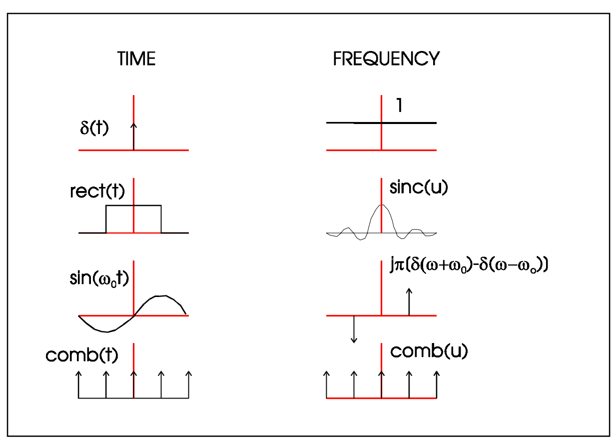

Figure 1. ***Useful Fourier Transform Pairs***

	x(t)		X(ω)
scaling	x(at)		X(ω/a)/|a|
shift	x(t-τ)		$X(\omega)e^{-j\omega\tau}$
convolution	x(t)*h(t)		X(ω)H(ω)
linearity	ax(t)+by(t)		aX(ω)+bY(ω)

Figure 2. ***Useful time-frequency identities***

For the purposes of this paper there's no need to actually solve a Fourier integral. We can predict a signal's spectrum using only a handful of transform pairs and a few identities as shown in figures 1 and 2.

Let's use these relationships to analyze two signals in both time and frequency domains. We'll start with a sine wave and multiply it in the time domain by a single pulse (rect). In the frequency domain, the spectrums of the pulse and sinusoid are convolved to produce a sin(x)/x type of response centered on the sine frequency. Note that the spectrum does not have any discrete tones associated with it. If we use a pulse train instead of a single pulse , then the spectrum has the same overall shape except that it consists entirely of discrete tones. We can think of the single pulse example as a time-selective power-spectrum analysis of the pulse train signal. Obviously, the time-selective spectral analysis of a single pulse in the pulse train will produce a different power spectrum than obtained when analyzing the entire pulse train. Is it wrong? Not necessarily. The limited observation interval has also limited the frequency resolution. This is a fundamental limitation that affects not only instrumentation, but receivers as well. This suggests that spectrum measurements must be designed for the system under test if results are going to be used to characterize system performance.

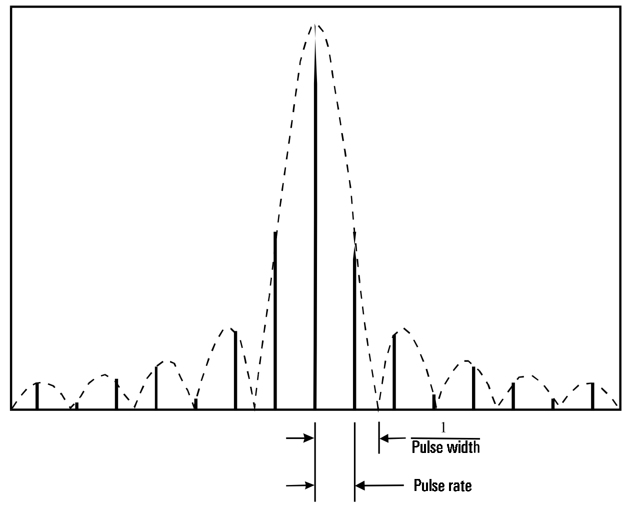

Figure 4. ***Spectrum sine wave multiplied by a train of rect functions.***

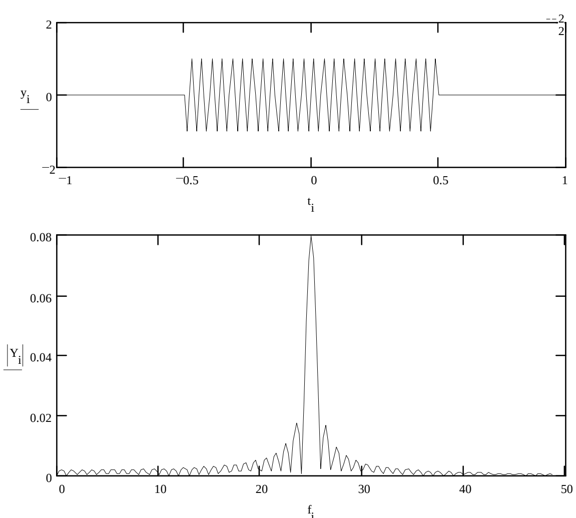

Figure 3. ***A sine wave multiplied by a rect function has a spectrum that is a sinc function convolved with a dirac delta function***

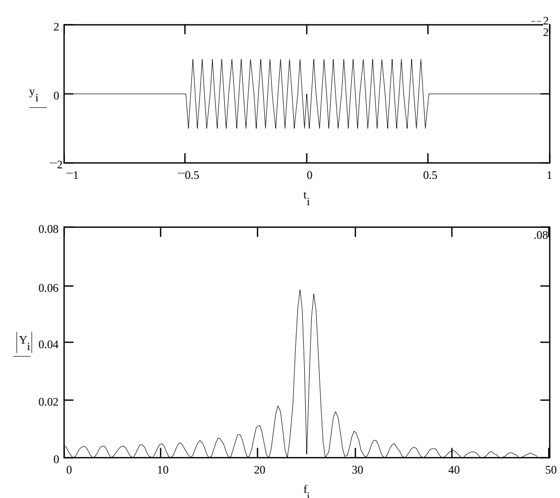

Figure 5. ***Sine wave multiplied by a rect function that changes polarity at t=0***

Consider the signal in figure 5. If we take a sine wave and multiply it by a bipolar pulse, that is, a pulse having a positive polarity over the first half of the pulse and a negative polarity over the second half, the resulting spectrum will be much broader than our previous example due to phase modulation of the sine wave. When the pulse changes polarity, the phase of the carrier also changes (in this case by 180 degrees), but the carrier power (integrated over one cycle) does not. (*Note*: In these examples the spectrum appears slightly asymmetrical because of the negative frequency image. If the carrier were at a higher frequency the sidebands would have diminished before reaching zero Hz.) Now, let's relate this signal to a real system.

Imagine a transmitter system that fails the adjacent-channel power (ACP) test. In this system, one designer carefuly controlled the amplitude profile of a pulsed power amplifier. Similarly, another designer worked to ensure that the filtering used to create the digitally modulated carrier was correct. Yet, when the modulated signal was passed through the amplifier and pulsing enabled, the system exceeded ACP limits. The cause? The pulsing of the power amplifier caused a phase disturbance in one of the local oscillators, which translated to extra phase modulation of the carrier during the turn-on transition. In this scenario, a time-selective power measurement will not show a problem. The power profile would look normal. A frequency selective power measurement will indicate a problem but will not help identify the cause. However, a time *and* frequency-selective power measurement will show that the excess ACP occurred at the carrier off-to-on transition.

Basic Power Definitions

Let's review some of the basic terminology associated power measurements. Whenever possible,the terminology associated with modulated carriers as defined in the *IEEE Standard Dictionary of Electrical and Electronic Terms* is used.

Instantaneous power is the time derivative of work, which for electrical circuits is equal to the product of the instantaneous voltage and current. If the voltage is applied to a purely resistive load, an assumption that will be used throughout the rest of this paper, then the power is:

$$p(t)=\frac{v(t)^2}{R}$$

For a carrier, the definition of instantaneous power is modified so that the power does not appear to fluctuate if the carrier is not amplitude modulated. This is achieved by defining the instantaneous power to be the power averaged over a carrier cycle. A more descriptive term would be *instantaneous envelope power*. Let v(t) be an amplitude and phase-modulated carrier.

$$v(t)=A(t)\cdot\cos(\omega\cdot t+\theta(t))$$

$$p(t)=\frac{A(t)^2\cdot\cos(\omega\cdot t+\theta(t))^2}{R}$$

The average power over one cycle of the carrier is:

$$p_{env}(t)=\frac{\omega}{2\cdot\pi\cdot R}\cdot\int_{t-\frac{\pi}{\omega}}^{t+\frac{\pi}{\omega}} A(\tau)^2\cdot\cos(\omega\cdot\tau+\theta(\tau))^2\,d\tau$$

It's often safe to assume that the modulation (both amplitude and phase) is slow relative to the carrier frequency. This allows the previous equation to be simplified.

$$p_{env}(t)=\frac{A(t)^2}{2\cdot R}$$

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Peak Power is defined as the maximum instantaneous power.

Peak Envelope Power (PEP) is defined as the maximum instantaneous envelope power which is the power averaged over a carrier cycle at the maximum amplitude that can occur with any combination of signals to be transmitted. Peak envelope power is often referred to as peak power.

Average Power is the power averaged over a specified time interval.

$$p_{avg}(t) = \frac{1}{T} \cdot \int_{-\frac{T}{2}}^{\frac{T}{2}} p(t+\tau)\, d\tau$$

Crest Factor is a ratio of the peak amplitude to the RMS amplitude, which is the square root of the ratio of the peak to average power.

The ***Mean Square Voltage*** is a quantity proportional to power. It can be calculated as the average power into a 1 ohm load.

The ***Root Mean Square Voltage*** is the square root of the mean square voltage.

The subject of ***Random Processes*** is too important to ignore, but it is also beyond the scope of this paper. The modulation of a carrier usually involves signals that can only be described by their statistics. In the time domain, the voltage ***variance*** of a signal is closely related to the mean square voltage and hence to the average power. In the frequency domain we deal with the ***Power Spectral Density*** *(PSD),* which is defined as the Fourier transform of the autocorrelation function. For practical applications, the PSD is a measure of the power contained in a unit of bandwidth (normally 1 Hz). By integrating the PSD over a range of frequencies we get the power in that frequency band. It's worth noting that the PSD is not useful with periodic signals (e.g. unmodulated carriers). A periodic signal can be expressed as a Fourier series (sum of sine waves), and the power in a sine wave occupies an infinitely narrow bandwidth.

Time-Selective Power Measurements

Time-selective power measurements determine the average power over a time interval. These measurements can be made with power meters, peak power meters, and frequency-selective instruments (swept spectrum analyzers and vector signal analyzers), provided the bandwidth of the instrument is wider than the bandwidth of the signal to be measured. Because time-selective power measurements are not frequency selective, the measured power will include contributions from the signal of interest, its harmonics and from noise sources both internal and external to the instrumentation.

The most fundamental time-selective power measurement is a measure of the average power over a long time interval. This very common measurement, most often made using power meters, is used to determine parameters such as the gain through a system, or the average transmitter power levels. For digitally modulated carriers, the average power does not typically vary with the information being broadcast. This is somewhat different than AM or SSB modulation, for example, where the power is a function of the statistics of the modulating signal (e.g. voice or music). For a single carrier system operating normally, a power meter may provide sufficient information about the peak power of a digitally modulated signal since the crest factor of a well designed system is a function of the design, and not the data being transmitted. It's important to consider the response time of the power meter, as the response time defines the time selectivity of the measurement. As an extreme example, a simple power meter responds too quickly to correctly indicate the average power of a signal that is on for ten seconds and off for twenty.

For pulsed signals, the average power measurement described above would be influenced by the signal's duty cycle. While one could measure the power averaged over a long interval (long relative to the repetition rate of the pulse) and then use an estimate of the duty cycle to determine the average power during the pulse, this is not recommended. The average power could be quite low relative to the average power during the pulse, and the duty cycle may not be precisely known. A better

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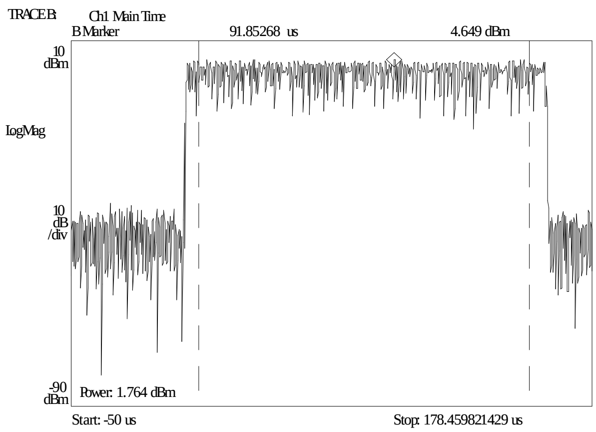

Figure 6. ***Magnitude profile (envelope) of a pulsed PI/4 DQPSK carrier showing the peak power and average power (while carrier is on).***

technique is to use instrumentation that can average the instantaneous power over a specified time interval. Peak power meters, swept spectrum analyzers with gating capability, and vector signal analyzers can perform this type of measurement.

With short integration times the measured power is considered to be the instantaneous power. By measuring the instantaneous power as a function of time, one can determine the peak power, the power distribution and the power envelope. The peak power in a digitally modulated signal is of obvious interest because of the linearity and headroom requirements in power amplifiers. The power distribution can be used in testing the linearity of power amplifiers, or in verifying the statistics of the modulation data.

The power envelope is extremely important in TDMA systems where both time and spectrum must be shared. A transmitter which has an envelope that is too long will interfere with another transmitter in an adjacent time slot. An envelope that's too short may prevent the data from being properly transmitted. Also, as will be demonstrated later, an envelope with fast rise and fall times may create adjacent channel interference. Determining the instantaneous power requires very short integration times. Although integration over one cycle of the carrier is desirable, it's usually impractical at the higher frequencies and is also unnecessary. The rate at which the power level of a carrier can change is a function of the bandwidth of the modulating signal. In other words, the integration time for the power measurement needs to be short relative to the dynamics of the modulating signal and is not, in general, a function of the carrier frequency.

In figure 6, a single marker is used to show that the peak envelope power during this pulse is 4.6 dBm. Band power markers are used to compute the average power while the carrier is on. This is displayed in the lower left corner as
1.8 dBm. Based on this one measurement (not a very good basis for the peak), the crest factor is 1.95. Note that because we are computing the average value of the power (not the energy) over a time interval , the spacing of the band power markers is not critical provided the carrier-off regions are avoided. Obviously the markers should be placed as far apart as possible to obtain the best estimate of the average power.

Frequency-Selective Power Measurements

All frequency-selective measurements attempt to determine the power of a signal within a specified bandwidth or at the output of a specified filter. As these measurements are not time selective, the results should correlate well with those predicted by the Fourier transform. For example, a frequency-selective measurement of a pulse-modulated sine wave will result in a spectrum with discrete spectral lines, with the line spacing equal to the pulse repetition rate. The frequency selectivity of the measurement is determined, not by the span, but by the resolution bandwidth filter (RBW), or more precisely its equivalent noise bandwidth (ENBW). For periodic signals which are comprised of discrete tones, the bandwidth over which the power is measured is of minor importance. As was mentioned earlier, the occupied bandwidth of a sine wave is infinitely narrow.

The measurement bandwidth *can be* significant if the power in the sine wave is not significantly greater than the noise power in that same bandwidth. Figure 7 shows how changing the RBW of a spectrum measurement causes the noise floor to drop,while the level of the unmodulated carrier remains fixed. This is true except at the widest RBW where the noise power add noticibly to the power of the sine wave. *Note*: This result may not be obtained with swept spectrum spectrum analyzers because behaviour of the log-amp/detector combination

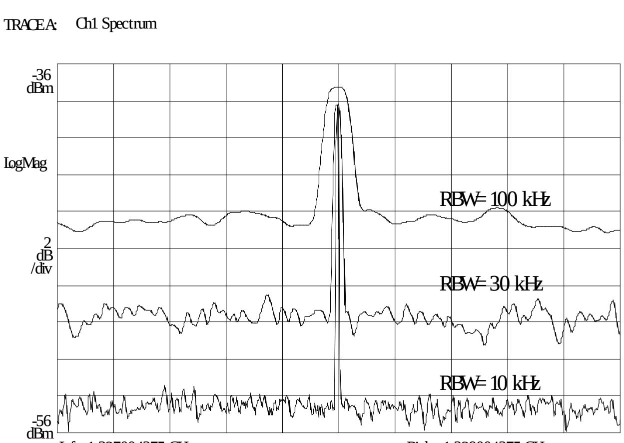

Figure 7. ***Spectrum measurements of a sine wave at three different RBW settings***

for a sine wave plus noise. A true-RMS detector was used for the measurement shown in Figure 7.

It's important to understand that the noise level in this measurement has remained constant. The decrease in RBW lowers the noise floor of the measurement because the power at each frequency point is integrated over a narrower bandwidth. In this plot the widest RBW is 100 kHz and the narrowest RBW is 10 kHz. Since the RBW

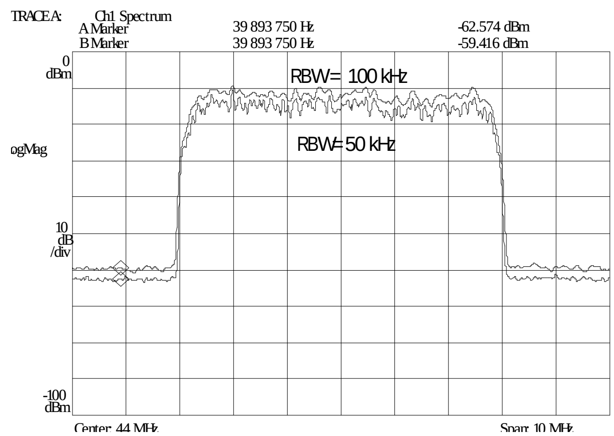

Figure 8. ***Spectrum measurements of a 32 QAM signal at two different RBW settings***

changed by a factor of 10, the noise power in the RBW filter has also changed by a factor of 10, or 10 dB.

Like noise, digitally modulated signals are also described by their PSD function. If you observe a power spectrum measurement and note the ratio between the in-band spectrum and the out-of-band spectrum and then change the RBW, the ratio will not change even though the absolute levels have. This is shown in figure 8. For this reason, when dealing with noise and digitally modulated signals, it's often more convenient to use the PSD function rather than the power spectrum. The PSD is the power spectrum normalized to a 1 Hz bandwidth and is normally computed from a power spectrum measurement by dividing the spectrum result by the equivalent noise bandwidth of the RBW filters. It's worth noting that if you're interested in the *ratio* of in-band to out-of-band power, e.g. an adjacent channel power ratio measurement, then the ENBW of the RBW filters is unimportant. However, if you are interested in making *absolute* power level measurements, then the filter's ENBW must be precisely known. The ENBW for

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a filter is generally wider than its RBW (depending on how RBW is defined). How much wider is a function of the filter's shape factor.
When making frequency-selective measurements it's important to consider the time interval over which the measurement is made. The time interval must be long enough to ensure that the measurement is not time selective. That is to say that the results will not change if the observation interval occurs at a different point in time, or changes in length. If you are unsure of the

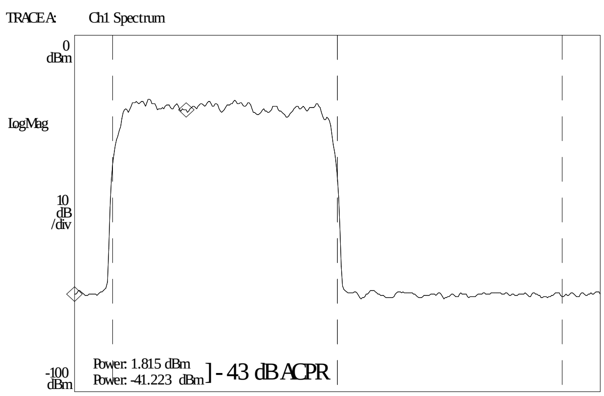

Figure 9. ***Measurement of the Adjacent Channel Power Ratio for a 32 QAM signal***

measurement, decrease theRBW to increase the integration time. The observed PSD should not change.

A very common frequency-selective measurement is the measurement of the power in an adjacent or alternate channel. Adjacent channel power limits are intended to insure that a transmitter does not interfere with another station on a different frequency. Figure 9 shows an ACPR measurement on a 32 QAM signal. The ACPR is computed by taking the ratio between the in-band power (power between left and center markers) and the out-of-band power (power between center and right markers).

In this example, the measured PSD in the adjacent channel is uniformly weighted and no allowance is made for a guard band. Some standards specify a weighting function (i.e. a filter). This is often done to make the measurement relate more closely to the characteristics of the receiver in a given type of system. In other cases, the filter specification matches the characteristics of RBW filters found in swept-spectrum analyzers -- for convenience. In these cases the power at the output of the filter is measured directly rather than integrating the PSD. For mixed and evolving systems (i.e. systems with more than one modulation format), such as might be found in a satellite transponder, the ACP measurements should not be weighted as the adjacent channel receiver characteristics may not be known or may change over time.

The most common approach to measuring power in a frequency band begins by determining the PSD and then integrating the PSD over the desired bandwidth. With this approach, a swept analyzer or a vector signal analyzer is configured with a relatively narrow RBW. The power at each frequency is divided by the equivalent noise bandwidth, or ENBW, of the selected RBW filter to get the PSD at that frequency. While several techniques are available to approximate integrals using sampled data (e.g. trapezoidal integration), with a sufficiently high number of frequency points the total power in a band can be approximated by multiplying the PSD at each frequency point by the span over which that value applies and then summing. The span over which each frequency point applies is usually the frequency point spacing -- except at the upper and lower edges of the band. Don't make the common mistake of confusing the spacing of the frequency point spacing with RBW or ENBW. As shown in figure 10, these are two different

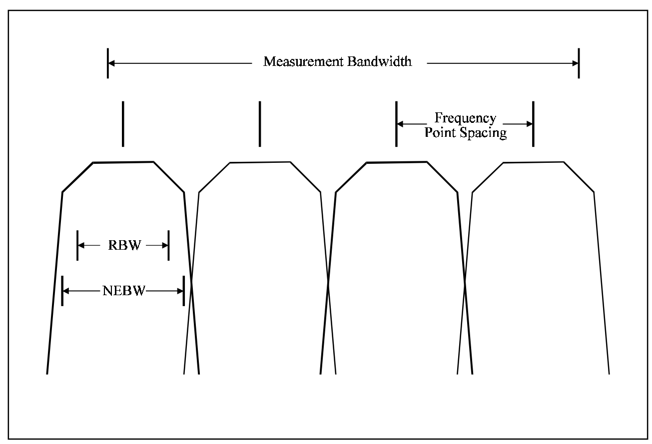

Figure 10. ***Relationship between frequency point spacing, RBW, ENBW and measurement bandwidth***

quantities. Also note that a wide ENBW could result in measurement inaccuracies because out-of-band power influences the observed in-band PSD near the edges.

Time and Frequency Selective Power Measurements

There are two distinct types of power measurements which are considered to be both time and frequency selective. The first is often called gated-spectrum analysis. In this type of analysis, the time selectivity is used to make a signal which is not uniformly distributed in time, look like one that is. This is analogous to looking at a clock once per hour so that, based on the hourly observations, it appears that the minute hand never moves. Gated-spectrum analysis is often performed on a pulsed signal to eliminate the spectral components associated with the on-off transitions of the carrier. In other words, the measurement never observes that the signal is pulsed. It can also be used to avoid portions of the signal that would appear to be periodic, such as a synchronization word. Gated-spectrum analysis results in spectrum measurements that are very similar to those that observed for a continuous (non-pulsed) signal. These measurements can be more accurately described as time-selective measurements of power versus frequency.

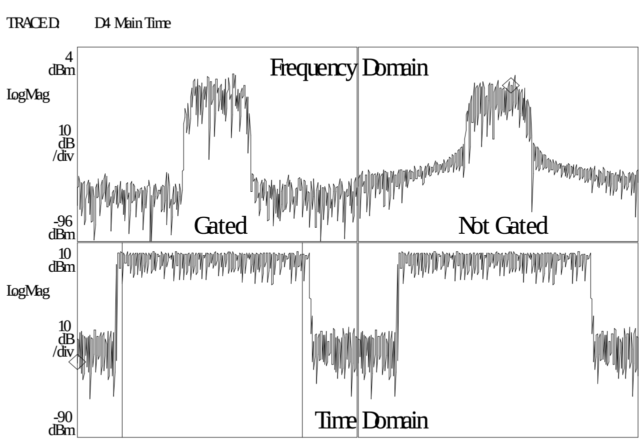

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Figure 11. ***Gating is used to perform a time***

Several different HP spectrum and vector signal analyzers are capable of making gated-spectrum measurements.

The plot in figure 11 shows two different spectrum measurements on the same pulsed PI/4 DQPSK signal. The upper, left contains a spectrum computed using the time data between the two time-gate markers shown in the lower, left trace. The gate markers were carefully positioned to avoid the on-off transients at either end of the pulse. The upper, right trace contains a spectrum computed using the time data over the entire pulse. As expected, the pulse modulation increases the bandwidth of the signal. Note that this is a spectrum measurement over a single pulse in a pulse train.

The second type of time and frequency-selective measurement can be described as a frequency-selective measurement of power versus time. In other words, the power in a frequency band, or bands, is recorded as a function of time. Under certain conditions a swept-spectrum analyzer can be used to make this measurement. These conditions include a power bandwidth that matches one of the available RBW filters in the instrument. To make the measurement, the swept analyzer is configured for a zero-span measurement with the center frequency and RBW set so as to determine the frequency band to be analyzed. The result is a plot of power verses time. Obviously, this approach allows only one frequency band to be observed at a time. Using overlapped FFT processing, a vector signal analyzer can measure hundreds of frequency bands simultaneously. At this point, an example of a frequency selective time measurement is in order.

In the measurement of the 32 QAM signal shown earlier, the ACP ratio was approximately 43 dB. By itself, this ACP ratio may not give all of the information necessary to determine if the ACP will cause interference. Also, if there's excess ACP, the previous measurement may not provide an indication to its cause. This is because frequency-selective power measurements do not take into account how the power changes over time. If most of the ACP is localized in time, then the potential for interference is greater. For example, the adjacent channel receiver might sustain an actual bit error on the peak interference, whereas the lower average level of interference may only increase the probability of a bit error.

As a demonstration, the 32 QAM signal (in figure 9) was intentionally modified to reduce the ACPR by 1 dB to 42 dB as shown in figure 12. The original spectrum and band power calculations are shown for comparison.

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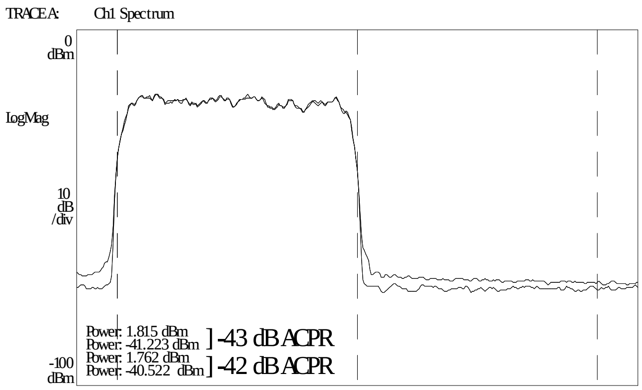

Figure 12. ***A problem introduces a 1 dB degradation in the ACPR for a 32 QAM signal. This measurement provides little insight into***

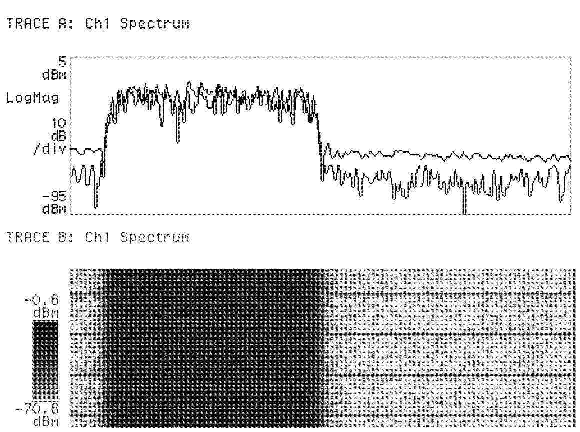

Figure 13. ***A Spectrogram comprised of many spectrum measurements indicates that the excess adjacent channel power is not uniformly distributed in time.***

Using the HP 89441A vector signal snalyzer's time capture buffer and a spectrogram display, it's possible to observe the temporal distribution of the power.

The top trace in figure 13 shows two spectrum measurements made at different points in time. Notice that the noise in the adjacent channel is higher for one of the spectrums. If we take the results of hundreds of spectrum measurements, evenly distributed over time and possibly even overlapping one another, we can create the spectrogram display shown in the lower trace. In this display each row of pixels corresponds to a

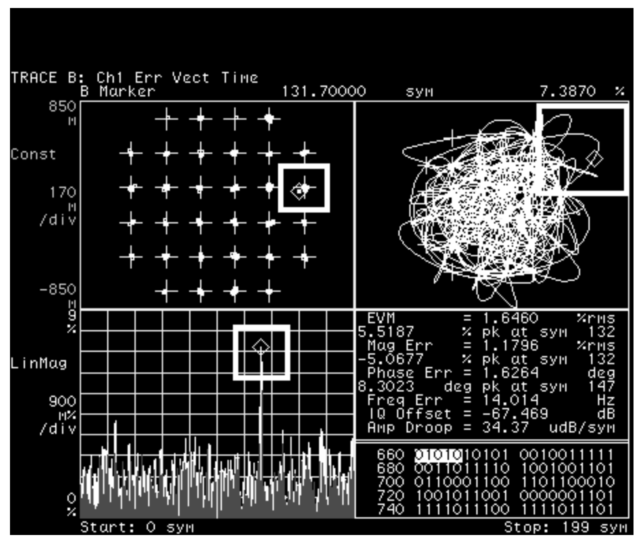

Figure 14. ***Plots of the demodulated signal uncover a large error at a single symbol location. This is the source of the excess***

spectrum measurement, so that time runs down the vertical axis, frequency runs across the horizontal axis, and amplitude is represented by intensity. A scale showing the mapping between intensity and power level is shown on the left side of the spectrogram. The four horizontal bands suggests that not only is the excess ACP very localized in time, but that it's also periodic. The periodicity of the ACP rules out an intermodulation distortion mechanism and strongly suggests an algorithmic problem. With this information the next logical step is to demodulate the waveform.

The lower, left trace in figure 14 shows a large peak in the error vector magnitude (EVM). EVM is the vector difference between a measured signal and an ideal signal transmitting the same data. Looking at the vector diagram in the upper right trace we see that the peak in the EVM is associated with a point in time where the carrier power is at a maximum. We can also see that one symbol in the constellation diagram is misplaced. This problem was introduced by mapping the maximum value that could be output to the digital-to-analog converter (used to generate the signal) to a value that was slightly smaller. In a real system this problem might occur if the scaling of the data for certain symbol combinations exceeds the maximum value supported by the digital-to-analog converters which generate the I and Q signals for the modulator.

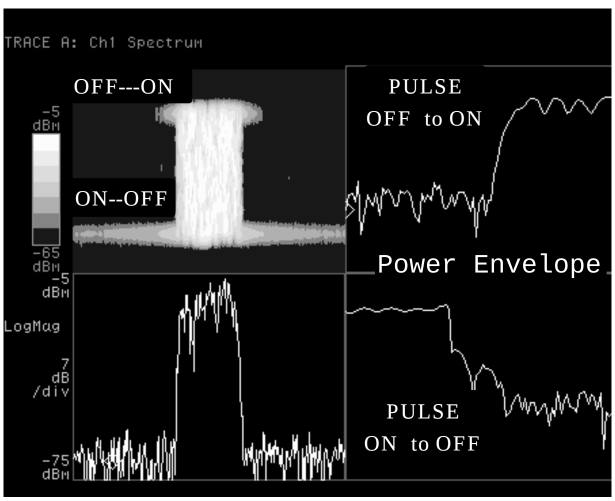

Figure 15. ***This spectrogram measurement shows how adjacent channel power is influence by the characteristics of the carrier off-on-off***

Earlier in this paper, we reviewed some of the basics concepts behind the Fourier transform and considered the different spectrums that would be obtained if we limited our observation time to a single pulse in a pulse train. We've also demonstrated that the inclusion of the on-off transients in a power measurement caused an increase in the measured bandwidth of the signal. Now, we will limit our observations to looking at a pulsed signal over an even shorter period in time. When we do this we're not interested in absolute power levels, but more in the temporal distribution of the power over a single pulse.

Figure 15 shows several measurements of the same $\pi/4$ DQPSK pulse. The traces to the right show the instantaneous power (as a function of time) during the off-to-on and on-to-off transitions at either end of the pulse. These are shown on a logarithmic scale. The lower, left trace shows a spectrum computed from the time data during the middle of the pulse. The upper, left trace contains a spectrogram comprised of over one hundred spectrum measurements. Each individual spectrum is computed from a block of time data that is 96% overlapped with the block of time data used to compute the previous spectrum. The spectrogram clearly shows that the off-to-on transition requires much less bandwidth than the faster on-to-off transition. As previously mentioned, the amplitude modulation is only part of the problem. Even if rise and fall times had been identical, phase modulation could have resulted in a similar spectrogram.

A Few More Words About Instrumentation

No one should be without a **Power Meter**. They are relatively inexpensive and make very accurate average power measurements on continuous signals. They are also very useful for calibrating test systems. The bandwidth of a power meter is both a feature and a detriment. Without frequency selectivity the dynamic range is limited because of the total noise power. Also, the measured power will include all distortion and spurious signals. This point should not be overlooked when using a power meter to calibrate a frequency-selective instrument like a swept spectrum or vector signal analyzer. A frequency-selective instrument will not observe the power in the harmonics and should return a lower reading.

Peak Power Meters suffer from the many of the same problems as a power meter, such as limited dynamic range. However, for signals with very wide bandwidths, the peak power meter may be the only instrument that can provide time-selective power measurement capability.

Swept Spectrum Analyzers are capable of making most of the power measurements described in this paper, several at the press of a button. Also, swept spectrum analyzers can have excellent dynamic range, an

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important consideration for measurements like ACP. Power measurements can be made on digitally modulated signals provided the inherent limitations of the logarithmic amplifier and detector are considered for the signal to be measured, and that the equivalent noise bandwidth of the RBW filters can be determined (for absolute power measurements). As will be discussed later, the phase noise performance of the spectrum analyzer may also be a consideration.

An HP 89441A **Vector Signal Analyzer** was used to make all of the measurements described in this paper. The VSA, which uses digitized time data as the basis for all of the measurements, is the only time and frequency-selective instrument capable of completely analyzing a single transient event. VSA's have good to excellent dynamic range and good to excellent phase noise performance. Because of its limited information bandwidth, the VSA has limited power measurement capabilities on signals with more than 7-20 MHz of bandwidth. In a VSA, the FFT window shape determines the characteristics of the RBW filter, so that the equivalent noise bandwidth is precisely known. Add to this the much improved shape factor, true RMS detection and RMS averaging, for accurate power measurements on *any* type of signal.

System errors

Although there is a trend toward using digital filters, most swept-tuned analyzers still use analog RBW filters. With analog filters the bandwidth of the filter can vary from nominal. For power-ratio measurements this variability will not usually cause problems. For absolute power measurements on noise and digitally modulated signals, the bandwidth of the filter must be known. For example, if the tolerance on the filter bandwidth is 10%, then the power at the output of the filter can be off by as much as 0.45 dB. This error would be in addition to any absolute level error observed for sinusoidal input. The shape factor of the filter is also a consideration. The RBW of a filter specifies its -3 dB bandwidth. With a standard 11:1 shape factor for analog filters, the equivalent noise bandwidth (ENBW) can be wider than the RBW by as much as 13%.

The RBW filter characteristics in a vector signal analyzer are determined by the FFT window. A traditional window, such as the Hanning window, will not provide adequate performance for most of the measurements described in this paper. The Gaussian window in the HP 89441A has a shape factor of better than 4:1 and stop-band attenuation (sidelobes) of better than 120 dB. As was already mentioned, the ENBW for the selected window is precisely known.

The diode detectors in peak power meters may give biased answers for non-sinusoidal signals with high crest factors. The amount of bias will be a function of the detector design, calibrations, and signal characteristics.

When using swept spectrum and vector signal analyzers you must be careful to consider the detectors. For example, a peak-hold detector would bias the answer, resulting in a larger than expected band-power reading. The amount of bias is dependent on characteristics of the signal to be measured, such as crest factor. Also, most swept analyzers have a logarithmic amplifier preceding the detector. For non-sinusoidal signals, the log-amp/detector combination can further bias the measured power. In vector signal analyzers the FFT provides a true RMS detector. However, when the VSA is configured for scalar mode operation (as opposed to vector mode), a detector may be used to reduce the number of frequency points displayed in the final result. Under these conditions it is possible to select a detector that will result in a biased answer. The sample detector should be used for band-power measurements.

The dynamic range of an adjacent channel power measurement is limited by the residual noise in the instrument, distortion introduced by the instrument and the instrument's phase noise. If the input level is decreased by 1 dB (using an attenuator), and the ACPR changes, then noise or distortion is limiting the measurement. If it doesn't change, then the measurement is either accurate, or it's limited by the phase noise of the instrument. For narrow-band systems the close-in phase noise performance of the instrument could be the limiting factor of the ACP measurement.

If the limiting factor is residual noise, then it may be possible to increase the dynamic range of the instrument by simply subtracting the residual noise power from the measured power. This is possible provided the noise is uncorrelated with the signal to be measured and also that the noise power can be accurately measured. This is most easily accomplished in the vector signal analyzer

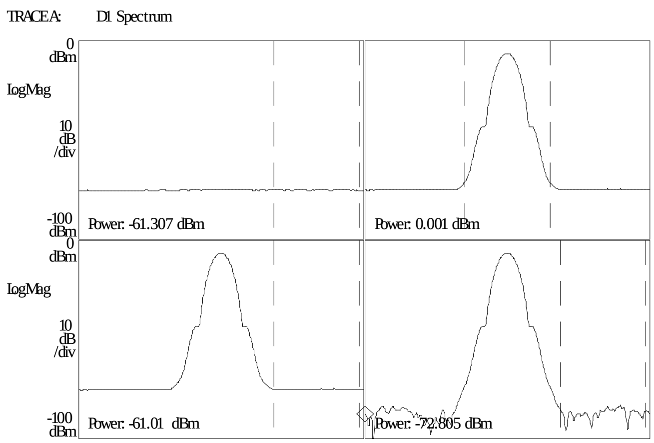

Figure 16. ***This ACP measurement of a GMSK signal was limited by the instrument's noise floor. The noise PSD was subtracted to improve the dynamic range of the measurement by more than***

because it offers true RMS detection, RMS averaging and extensive trace math capabilities.

To increase the dynamic range in the HP 89441A, for example, a measurement of the residual noise is made by disconnecting the input signal and providing proper termination of the input. After a sufficient number of averages have been made, either the spectrum or PSD is saved into one of the data registers. The signal is reconnected and another averaged spectrum or PSD measurement made. If the PSD was saved, then a math function which simply subtracts the noise PSD contained in the data register from the measured PSD will produce the desired result. If the spectrum was saved, then the math function will calculate the square root of the square of the measured spectrum minus the square of the noise spectrum (in the data register). The squaring operation is necessary to ensure that power, not volts, is used in the equation.

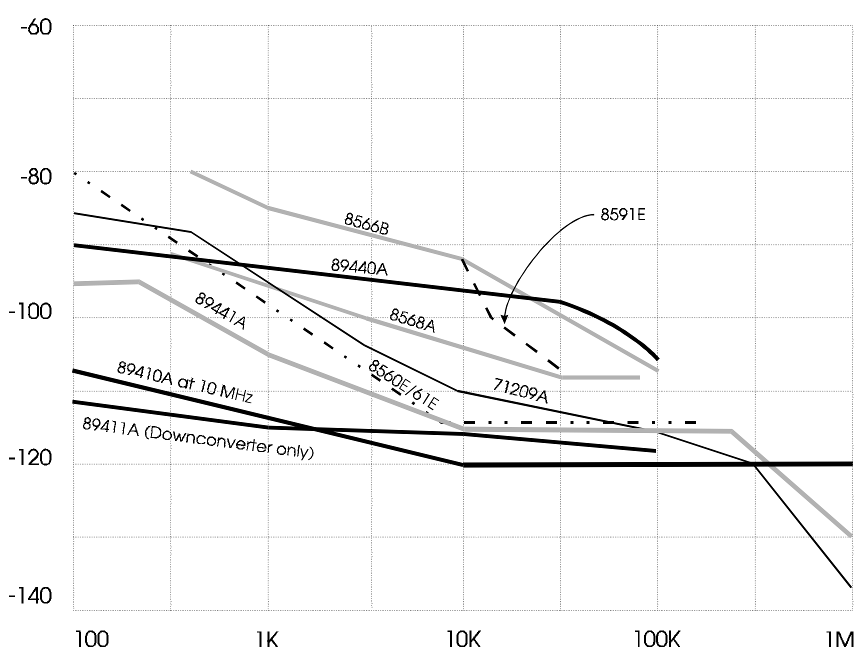

Figure 17. ***Phase noise comparison for several different HP swept spectrum and vector signal analysers.***

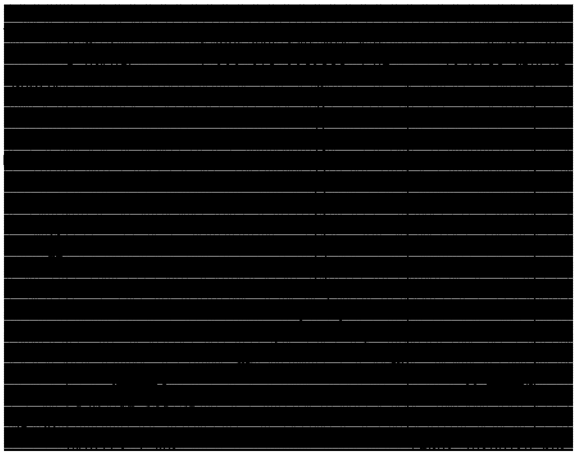

Figure 18. ***Phase noise increases the measured adjacent channel power.***

The measurement of a GMSK signal shown in figure 16 provides a graphic example of the dynamic range improvements that are possible using the noise subtraction technique. The original measurement was limited to a 61 dB ACPR. By subtracting the instruments noise power (as shown in the upper left trace), the ACP decreased by 11 dB resulting in a 72 dB ACPR.

Phase noise can limit an instrument's ability to measure power in a band near the carrier. The plot in figure 18 shows a distinct phase noise pedestal on what is supposed to be an unmodulated carrier. The band power markers are used to measure the carrier-to-noise ratio, which is shown as 67 dB. If the analyzer had contributed the phase noise, then 67 dB may be the best CNR that can be measured in that band.

Often, phase noise is specified at a single frequency offset. In this measurement, a second marker shows the PSD halfway between the band power markers as -104.8 dBm/Hz (relative to a 0 dBm carrier) or -104.8 dBc/Hz. If we were to assume that the PSD was constant over the same 5 kHz span that's measured using the band power markers (which it obviously isn't), then we would determine that the CNR is $-104.8 + 10*\log(5000) = -67.8$ dB, which is 0.8 dB too low. This shows the danger in relying on a single frequency point phase noise specification.

The phase noise specification for both swept spectrum and vector signal analyzers is very important, especially for measurements on narrow-band systems. In the previous example, we need to determine whether or not the ACPR measurement is limited by the phase noise performance of the analyzer. In figure 17, we see that the worst case phase noise for the HP 89441A over a 5 kHz band centered on a
6 kHz offset is less than -115 dBc/Hz, or approximately 10 dB below the measured value (at the 6 kHz offset). This would suggest that we have an accurate measurement of CNR, provided that we aren't noise floor limited.

SUMMARY

Power measurements on digitally modulated signals can be time-selective, frequency-selective, or time and frequency selective, with each measurement providing a different perspective on system performance. While frequency- selective measurements can be used to discover a problem, such as excess ACP, isolating the cause of the problem may require a measurement that is selective in both domains.

A digitally modulated signal has characteristics similar to noise, both in terms of its PSD and amplitude distribution. This is an important consideration, since all instruments are not equally suited to the task of accurate noise-power measurements.

Power Measurements on Digitally Modulated Signals

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