Measuring digitally modulated RF signals

Part I-Multipath reflections cause more problems with digitally modulated RF signals than with analog-modulated signals. In this installment, flat fading and frequency-selective fading are explained.

By James Bush, Ph.D.,
and Gary Schober

Digitally modulated radio-frequency (RF) signals manifest unique characteristics at personal communications (PCS) frequencies when they are reflected. Reflections add out-of-phase data symbols that cause bit errors. Paradoxically, simple signal-strength measurements at PCS frequencies (using signals with a narrow bandwidth, such as a continuous wave [CW]) can be deceptive because, although the signal may even appear to be quite strong, when it is digitally modulated, the bit-error rate (BER) performance may be poor.

Multipath reflections (multipath, for short) of the RF carrier are better known as *time dispersion* or *delay spreading*. Time dispersion or delay spreading occurs when a single signal travels from its source to the receive antenna via two or more paths of different lengths. One part of the signal may come directly; the others have been reflected during their travel and take longer to reach the receive antenna. The effect is as though two or more individual signals with identical modulation reach the receive antenna, but with the modulation having been offset, or *delayed*, by various intervals of time. Reception of a signal affected by time dispersion is deteriorated. Reflections must be considered when planning and optimizing digital radio systems that use high data rates.

Characterizing an RF channel's delay spread determines whether the energy on the radio channel is affected by *flat fading* or *frequency-selective fading*. Flat fading means that all frequency components transmitted through the channel bandwidth are affected by the same magnitude of fading. Conversely, frequency selective fading, also known as *differential fading*, means that some parts of the channel bandwidth are affected by greater fading than other parts. If the channel is not flat, then a signal equalizer is required at the receiver to maximize the system performance for any given data rate and carrier frequency. Generally, a channel is considered flat when:

$$\frac{Y}{T} < .01$$

where

Y = root mean square (RMS) delay spread
T = symbol period

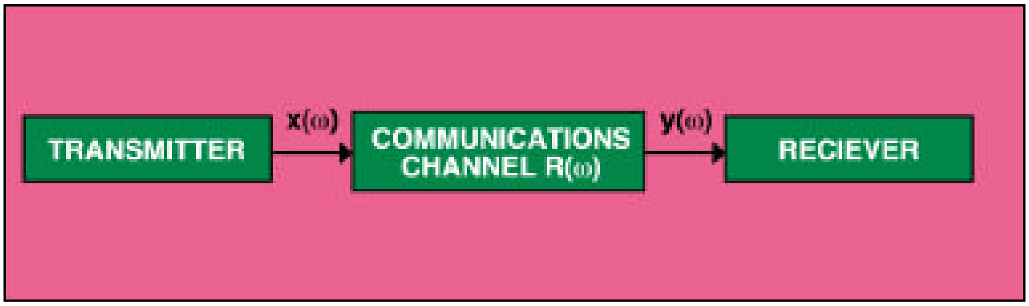

Figure 1. The Communications channel is considered to be linear and time-independent with frequency responses R (ω).

Higher frequencies and digital wireless technology developments have made it necessary for RF engineers to broaden their knowledge of radio propagation. Today's designers are finding it necessary to better understand what causes compound signal distortion of digitally modulated RF signals and to keep current with propagation phenomena that affect them. Actual propagation measurements provide data from which time dispersion effects and path loss can be calculated. Decisions concerning antenna placement, base station location, antenna directionality, power remediation and channel reuse efficiency all are influenced by real-world measurements.

Time dispersion can be characterized by excess delay, mean excess delay and RMS delay spread. The path-loss exponent and standard deviation can characknown model in a log-normal shadowing environment.

To examine the effects of multipath on - < 0.1 RF communications, the RF communications channel is con-

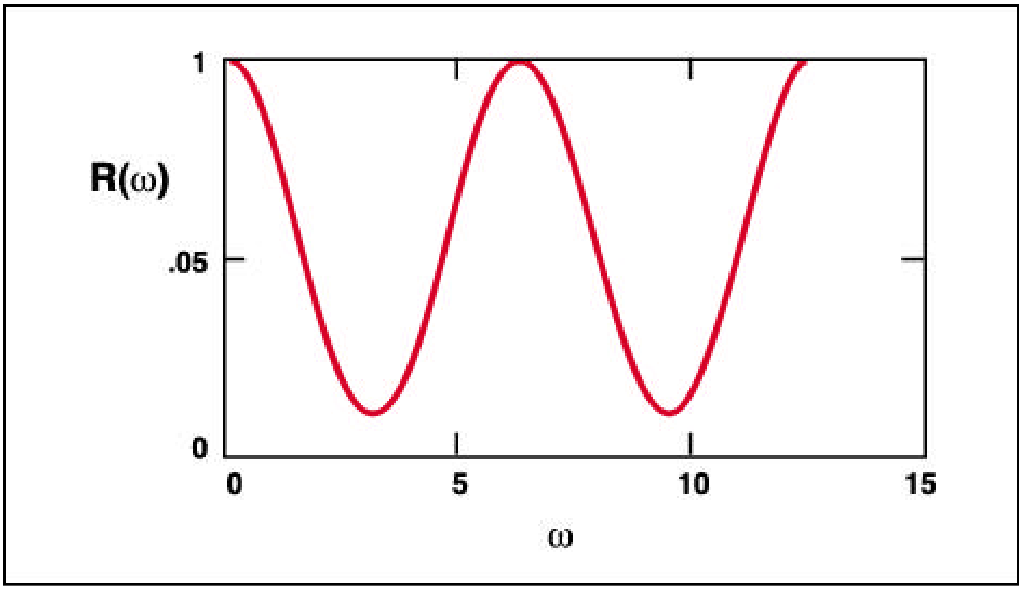

Figure 2. The magnitude of the channel frequency response in the presence of a single multipath.

sidered as though it were another system element. For simplicity, the communications channel is considered to be linear and time-root mean square (RMS) delay spread independent with an impulse response $r(t)$ and a frequency response $R(\omega)$. (See Figure 1 on page 1.) An RF communications channels properties vary over time, so it clearly is not time-independent; nevertheless, for the purpose of understanding multipath effects, it is convenient to ignore its time-dependence as an unnecessary complication and to consider small periods during which the channel's properties are stable.

Overlooking for the moment the effect of distortion and considering only the effect of multipath, the signal at the receiver, $y(t)$, is the sum of the delayed versions of the original transmitted signal, $x(t)$. For example, with only two multipath signals:

$$y(t) = P_0\, x(t - T_0) + P_1\, x(t - T_1)$$

where T_0 and T_1 are the delays of each path, and P_0, and P_1 are the corresponding received signal strengths. The sum could correspond to a direct path delayed T_0 seconds and a reflection from a nearby building with a total path delay of T_1 seconds.

Because the system (channel) is considered to be linear, the impulse response of the channel is enough to characterize it. In the example, [where $\delta(t)$ is the delta function, an impulse at the origin] the impulse response would be:

$$r(t) = P_0\, \delta(t - T_0) + P_1\, \delta(t - T_1)$$

The absolute delay of the signal does not contain as much inform difference between arrival times of the multipath components. This difference, τ, determines the manner in which the transmitted signal is changed. In this simplified case, small values of τ correspond to close-in multipaths in the general case, where all of the multipaths arriving at the receiver near the time of arrival of the strongest signal. Larger values of τ correspond to channels that have a large delay spread.

Rewriting the impulse response and showing the frequency response of the simplified channel in terms of τ yields the following mathematical result, which can be interpreted to understand much about the general case:

$$r(t) = P_0\, \delta(t - T_0) + P_1\, \delta(t - T_1 - \tau)$$

$$R(\omega) = P_0\, e^{-t\omega T_0}\,(1 + \frac{P_1}{P_0}\, e^{-t\omega\tau})$$

$$|R(\omega)|^2 = P_0^2[(1 + S^2 + 2S\cos(\omega\tau)]$$

where

$$S = \frac{P_1}{P_0}$$

Most important is the magnitude of the channel's frequency response. The frequency response is shown normalized in Figure 2. The width of the power peaks depends on the value of τ. The smaller τ, or in the general case, the delay spread, the larger the bandwidth of those peaks. The depth of the valleys is determined by S, the ratio of strength of the largest signal, which is referred to as the *main signal*, to the strength of the multipath component.

Referring to the equation, notice that this variation is periodic with period τ - in fact, it is offset cosine wave form. This variation means that, for large τ, there are many close-together peaks, and for small τ, the peaks are farther away from each other.

The addition of a multipath component changes the communication channel from a loss-only device to a frequency-selective filter; therefore, the communications channel actually rejects certain frequencies. The addition of more multipath components will change the spectral response of the channel, although it will, in general, be some sort of frequency-selective filter.

If the signal strength of the multipath component is low, relative to

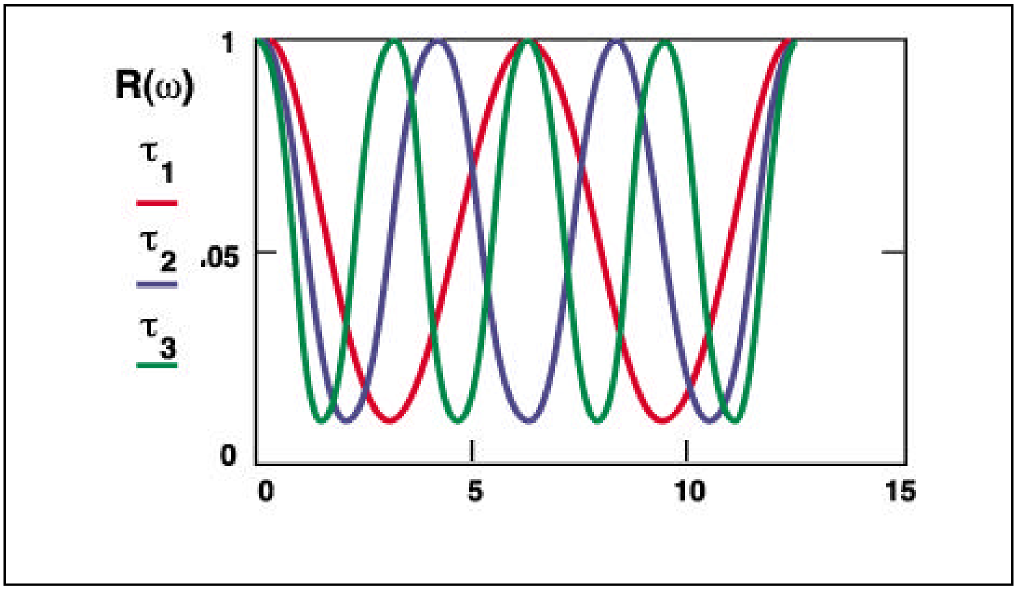

Figure 3. In a mobile environment, as the receiver is moved around, the difference between the two paths changes constantly, and the peeks in the channel's frequency response slide back and forth. The shifting frequency response causes the signal strength at the receiver to fade in and out.

the main signal, then the valleys are shallow and are not of much concern. When the multipath signal strength approaches that of the main signal, the valleys become deep, and they can interfere with communication.

When the widths of the peaks in the channel's response are much larger than the bandwidth of the information on the channel, the frequency components of the entire signal are attenuated by about the same amount. The amount of attenuation may be small if the information happens to be positioned on a peak, or severe if the information is in a valley. This type of attenuate is known as *flat fading*. In a mobile environment, as the receiver is moved around, the difference between the two paths changes constantly, and the peaks in the channel's frequency response slide back and forth (See Figure 3). The shifting frequency response causes the signal strength at the receiver to fade in and out.

If a channel does not exhibit flat fading, different frequency components of the signal are attenuated by different amounts. This type of signal strength variation is called *frequency-selective fading*. In an extreme case, ranges of the frequency spectrum of the information can be notched out, with disastrous results for the received signal.

Communications channels, especially in the mobile environment, generally are surrounded, or measured, with continuous wave (CW) transmitters and narrowband receivers. Unfortunately, the only multipath information that can be detected with this type of measurement is the presence of low signal strength at the carrier frequency, which could be caused by path loss or flat fading. CW measurements do not detect frequency selective fading if the attentuated, which means that areas validated with CW measurement equipment may be unusable for communications.

With the growing deployment of digital PCS equipment, these considerations become even more important. Many of the digital communications techniques, such as code-division multiple access (CDMA) and global system for mobile communications (GSM, formerly Groupe Speciale Mobile), use high data rates and, consequently, large bandwidths. The use of large bandwidths makes these systems particularly vulnerable to frequency-selective fading. Compounding the problem, the licensed PCS frequencies are near 2GHz. Signals in this frequency range exhibit a lot of multipath because many outdoor surfaces reflect energy at 2 GHz.

Although these results are not new, until recently, no affordable commercial equipment could measure multipath information. With current equipment, multipath information can be gathered as easily as making CW measurements.

Figure 4 on page 4 shows a signal without multipath components. It shows a real-time display of multipath information. The horizontal axis shows the power of the signal component arriving at that time. The small bumps near the main peak actually are the impulse response of the transmitter's output filters. These filters smear the data in time for the purpose of band-limiting the output spectrum.

Figure 5 consists of a close-in multipath and a multipath considerably farther away, The more distant multipath can cause valleys in the spectrum every 300kHz. The figure's scale is linear, so this multipath component is nearly the same amplitude as that of the main component. This image was captured in an area where a GSM system was having difficulty communicating with mobile units. The bandwidth of a GSM signal is 200kHz.

Figure 6 shows three close signal

components with nearly the same amplitude arriving at the receiver at different times. Such a condition would be Communications Specialists likely to cause severe flat fading for low bandwidth systems and severe frequency-selective fading for higher bandwidth systems. Note that a CW measurement might show the signal strength to be the sum of all three signals.

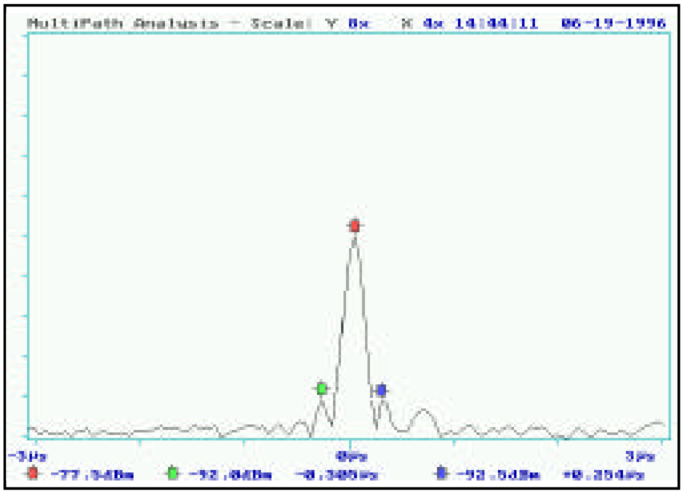

Figure 4. A signal with negligible multipath components.

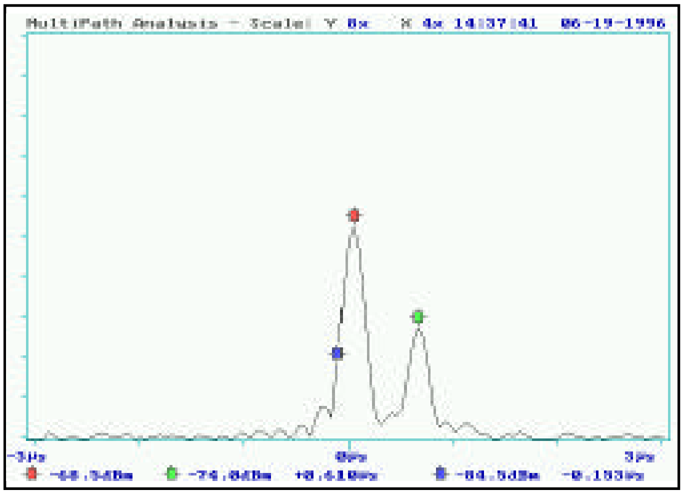

Figure 5. Multipath components are close-in, and are decaying with increasing delay.

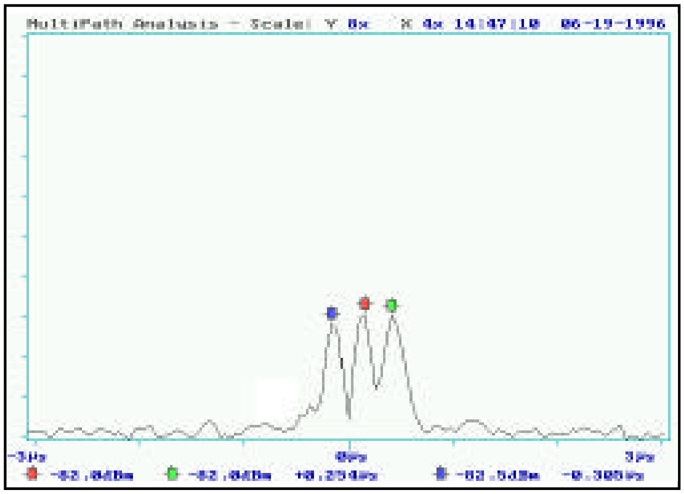

Figure 6. Severe intersymbol interference.