Resolving Interference in the Unlicensed Bands
Using a Spectrum Analyzer

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Among motorcyclists there is a saying: "There are only two kinds of riders–those who have gone down and those who are going down"; sooner or later, everyone who rides falls. Similarly, *If you operate a wireless system within one of the unlicensed bands, sooner or later your link throughput and availability will be compromised by interference.*

The use of the unlicensed bands has become a very popular way to provide access to the Internet (Wi-Fi, WISPs) and to realize an inexpensive and rapidly deployable wireless LAN. In addition, new technologies promise to provide access to even more customers (Wi-MAX, Mesh). The FCC and USDA have together entered the act with a new program (VISION) to promote wireless access in rural areas. However, this ever-increasing deployment of unlicensed radio links brings with it a serious problem: potential interference from other unlicensed radios.

Licensed radio link operators normally don't suffer interference from other operators, thanks to frequency coordination requirements by the FCC. Licensed link availability issues are almost always weather- and path-induced. If a licensed radio operator does encounter interference, it is usually from some illegal RF source, and the licensed operator can have the FCC resolve the problem and go after the offender. Unlicensed operators don't have this kind of protection. They must find their own ways to mitigate interference problems. Doing on-site interference measurements and analysis can be the only realistic and reliable way of identifying and resolving interference for the unlicensed operator.

This paper will first present some preliminary information on interference and how radio receivers are affected by the various kinds of interference. This will be followed by some general information on spectrum analyzers and their functions relating to interference measurement, capture, and analysis. Then we will address the major issues involved in using a spectrum analyzer for on-site interference analysis; provide some general link engineering information; and, finally, offer suggestions on mitigating or avoiding interference when operating in the unlicensed bands.

System Instability. *In deploying unlicensed systems, the three leading causes of system instability, other than equipment failure, are:*

1. Excessive path length
2. Excessive antenna height
3. RF interference

Excessive path length. Many wireless equipment manufacturers claim 25- to 50-mile path distances for their non-diversity equipment. It is a fact that in the United States and Canada, the maximum 5 GHz path distance for a reliable non-diversity system is about seven (7) miles and, over time, this could decrease with the increasing deployment of wireless systems. For example, a 2.4 GHz system operating over a 30-mile flat-terrain path requires the antennas to be placed 190+ feet in the air…just to clear the earth's bulge. And, using an 8-foot antenna, the beam width would be 3.6 degrees, which, at 30 miles away, is 1.9 miles wide. The victim radio's window for receiving interference is enormous.

Excessive Antenna Height. In many unlicensed systems being deployed today, there is too much emphasis on line-of-site. Although sufficient Fresnel clearance from obstructions is important, in trying to attain an absolutely clear path, system designers and installers often employ excessive antenna height ("If high is good," they think, "higher would be better"). But when antennas are placed higher than required, unpredictable system outages can occur. Excessive height opens the victim radio's view to more sources of RF interference from distant sites as well as to multi-path reflection issues caused by clearing even-numbered Fresnel zones.

Note: The earth's curvature, as well as atmospheric conditions, can refract or bend electromagnetic waves. Normal atmospheric conditions provide a radio horizon that is actually farther away than the visual horizon. This curvature is not normally an issue for paths under 10 miles.

RF Interference. Interference is defined as: "extraneous signals of any kind (noise or other radio signals) that contribute to the degradation or reduced intelligibility of the desired radio signal." Radio communications can experience several different types of interference. They range from static thermal noise to inter-modulation noise caused by the blending of two or more signals. Static thermal noise can be addressed through proper system design, which ensures that adequate fade margin is built into the system. Inter-modulation noise, on the other hand, is the classic form of interference that, sooner or later, confounds most unlicensed systems.

A common misunderstanding is that system availability numbers, such as "five nines" (99.999%), derived from path analysis software, are achievable as long as the calculated fade margin is met. These availability numbers assume only atmospheric fading. They do not include the effects of reflective fading (multi-path) or interference from other intentional radiators. To really know the extent of potential interference sources, as well as the available signal strength from your remote transmitter to your intended (victim) receiver, you need to do an analysis of the real-world conditions present at your intended receiver site. This analysis should both measure interference across the spectrum of interest and transmit channel power at the receiver site. The best way to do these measurements is with a spectrum analyzer.

Types of Interference. The conditions that create interference are unique to each individual case. There is no standard level of interference nor is there a single formula that can be used to compute it. What constitutes interference in one system may be totally invisible or inconsequential in another. To understand interference within its unique environment, we need to define it in terms of its amplitude relationship to the amplitude of the desired or carrier signal. This relationship is known as a carrier-to-interference ratio (C/I), and is quantified as decibels or dB. Given the proper application of their measurements functions, some Spectrum Analyzers can derive real-world C/I.

C/I. Every communications receiver has a minimum carrier-to-interference ratio that must be maintained in order to recover 100% of the information from a desired signal. If this minimum ratio of signal over interference is not met, communications will be disrupted and the system may become unusable. The specific receiver C/I characteristics depend on the usable dynamic range of the receiver's front-end, on the type of demodulator and modulation schemes, and on the error correction being employed.

IM Distortion. Dynamic range problems occur when the front-end of the receiver is not properly designed, or when it is subjected to RF overload from strong signals—which can cause inter-modulation distortion or degradation of the threshold sensitivity of the receiver. In cases of inter-modulation distortion, inter-modulation products confuse the demodulator in the receiver so that it is unable to discriminate between the real signal information and the phantom inter-modulation signal components. Result: garbage output or system crash.

IM distortion occurs when a transmitter on a nearby RF channel is located to close to the receiver. In cases involving receiver inter-modulation interference, the transmitter does not even have to be on the receiver's frequency. This situation is most common at sites where multiple co-located transmitters are operating within the same frequency band. The problem is exacerbated when multiple co-located transmitters employ time-domain duplex techniques to utilize the same frequency in both transmit and receive directions. This scenario would most likely occur with 2.4 and 5.7 GHz wireless LAN (WLAN) equipment that utilizes this type of transmission technology—regardless of whether direct-sequence or frequency-hopping spread spectrum techniques were used.

To make matters worse, antennas are frequently installed within each other's near-field boundary where, because of cross coupling, the antenna radiation-pattern and gain characteristics are degraded—and so no longer meet the performance criteria of their manufacturer.

Frequency Interference. Assuming that the interference is not RF overload-induced, the other type of carrier-to-interference problem is easier to deal with, since it involves an interfering signal that occurs at the receiver's input frequency. In such cases, the problem can be easily diagnosed and quantified, because interfering signal strengths can be computed and compared to the desired signal. And that, in turn, allows a solution to be defined. Since all antennas involved are operating at far-field, their known gain and radiation-pattern characteristics can be applied when computing the required adjustments applicable to the paths involved. The objective then becomes one of computing carrier-over-interference ratios for all receivers involved—basing the computing on all transmitters involved and taking into account the path losses and antenna gains for each path.

Thermal-Noise & Interfering Signals. Thermal-noise and an interfering signal differ in nature. An interfering signal has coherent characteristics, unlike thermal-noise that is Gaussian (random) in nature. Because of its frequency relationship and coherent characteristics, an interfering signal is capable of causing destructive interference, even at levels below the thermal-noise threshold of a receiver. Whenever a coherent receiver's demodulator acquires and locks on to a signal within its tracking bandwidth, an interfering signal—which would normally be hidden in the noise—becomes a factor. Anytime the difference in magnitude between the two coherent signals becomes small enough, the resulting inter-symbol interference confuses the demodulator, rendering it unable to track the desired signal. Accordingly, it loses lock. This power relationship between the carrier and interference signals = the C/I threshold of a receiver, specified in decibels.

When is Interference a Problem? In microwave wireless links, interference has been traditionally considered a problem when it causes a BER (bit-error rate) of 1 bit per 1 million bits transmitted ($1 \times 1 \text{x} 10^6$). Thus, the Telecom industry found that for digital microwave signals, a BER of $1 \times 1 \text{x} 10^6$ produced a pop in the customer's headset twice a minute--the maximum acceptable bit error rate. This standard is still in use today by microwave radio manufacturers. Lamentably, for it is retro. Anytime interference renders a system unstable, it violates the only standard worth worrying about.

Spectrum Analyzers. A Spectrum Analyzer is a valuable piece of test equipment that can be of great help in *seeing* signals across a spectrum of frequencies. Unlike an oscilloscope, which displays signals relative to *time* (time domain), a spectrum analyzer displays signals relative to a spectrum of *frequencies* (frequency domain). These instruments display electromagnetic energy by frequency in real time and have a variety of adjustments and settings that allow the operator to measure and display the energy within groups of frequencies (resolution bandwidth) contained within a defined bandwidth (span).

When selecting the instrument's parameters:

- The broader you set the Resolution Bandwidth the greater the noise floor.
- The narrower the Resolution Bandwidth, the longer the measurement time across the Span of frequencies.

The wider the frequency spectrum, the more noise there is within this spectrum. This noise is summed together and displayed as the noise floor of the instrument, limiting the ability of the instrument to display small signals. By setting the Resolution Bandwidth to a small window of frequencies you will achieve better sensitivity (lower noise floor) but at the expense of longer measurement times. Setting the Resolution Bandwidth to a larger frequency window will achieve a faster measurement time across the Span but at the expense of small signal sensitivity. Therefore the setting of Resolution Bandwidth is a compromise between a low noise floor and faster sweep times. For unlicensed radio use, a Resolution Bandwidth setting of 1 MHz with a Span setting of 100 MHz is a good compromise that will capture all the channels from frequency-hopping radios within a reasonable time. There are many more functions on most full-featured analyzers, but *Span* and *Resolution Bandwidth* are the two of primary interest in analyzing radio interference and measuring the performance of wireless links. Now let's look at how to *use* the analyzer for site analysis.

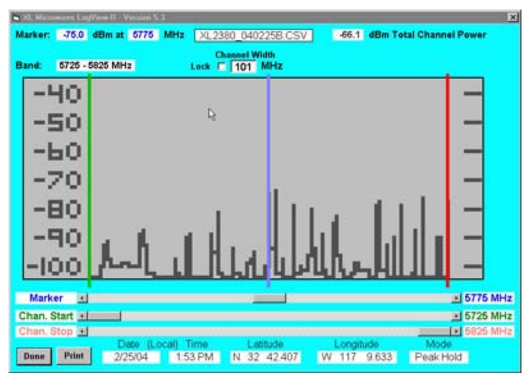
Site Analysis Using a Spectrum Analyzer. If you had access to C/I performance information from the radio's manufacturer and a spectrum analyzer *with an adequate dynamic measurement range and noise floor,* you could measure the interfering signal level at the input to the affected receiver. You could also measure the radio's carrier power. You would then use the comparison between the published C/I requirement and the measured C/I at the site to quantify the severity of the interference problem.

Interference Measurements (radios off). First, you need to make a baseline measurement of all the energy present at your proposed site. This is not only useful for determining the best location for a site but also for historical purposes, as a reference for down-the-road problem analysis.

Omni Antenna. It is recommended that you start with an omni-directional antenna attached to the input of the spectrum analyzer in order to see the entire world of interfering sources that exist at the proposed victim receiver. Needless to say, this measurement should be done with the radios off. When doing interference measurements with a spectrum analyzer it is necessary to look over an extended period of time (10–15 minutes minimum), using the Peak Hold mode on the analyzer. If given enough time, the Peak Hold mode will capture all of the hopping and time-division duplex radio interference. Without sufficient viewing time you can have gray-out (missing data due to analyzer sweep-time and hopping dwell-time conflicts). Because of the way spectrum analyzers work (sweeping the preset Resolution Bandwidth across the Span) the analyzer can repeatedly miss a hopping channel without capturing the energy in that channel. The analyzer will eventually sweep over the radio's hopping channel, just as the radio is transmitting, and capture the energy–but only if it has many chances to do so.

At the right is an example of an interference sweep taken with a Model 2261 Analyze-R™ from XL Microwave, using an omni antenna. The sweep is of a 100 MHz-wide Span (5.725–5.825 GHz) with a Resolution Bandwidth of 1 MHz, in Peak Hold, showing numerous hopping channels.

Note: The FCC has mandated that hopping frequency dwell time be less than 400 ms (max). The Analyze-R™ band sweep time is 300 ms. Sweep times for general purpose spectrum analyzers may be even longer, depending on the Resolution Bandwidth setting (finer resolution = longer sweep times).

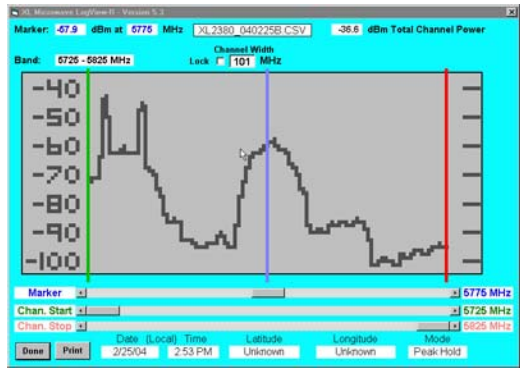


Directional Antenna. Once a general "Omni" sweep of the frequency band of interest has been done, you should then use a directional antenna to locate the direction and source of any potential interference the omni sweep found. Knowing the source location can help you determine how and where to deploy your antenna. The best way to accomplish a complete interference map is to do a polar plot of the source and direction of the interference. You can accomplish this by using a directional antenna with approximately a 10° beamwidth oriented with vertical polarization. Use a compass to locate magnetic north, point your directional antenna north, and record a spectrum sweep–noting the antenna's azimuth (0°). Remember to allow the analyzer to "look" for a minimum of 10 minutes. Rotate the antenna 10° and record the next sweep, noting the antenna's azimuth. Continue this routine till you have a complete 360° polar plot of the interference. You should then repeat this process with the same antenna horizontally polarized. You now have a complete polar plot of the interference spectrum at your site, and you can use this information to pinpoint the source location. Latitude and longitude coordinates must be known for your site location in order to accomplish source location. This information can be obtained using GPS equipment, or by identifying the site locations on a map that provides latitude and longitude information, such as USGS 7.5 minute topographical maps. Alternatively, computer-map software such as Microsoft Streets and Trips, or Delorme's Street or TOPO map-software, all have location sensors built into the program cursor.

When you locate a source, you should note the results of changing the antenna polarization. The interference may be mitigated by going from a horizontal to a vertical polarization. A higher-gain antenna, with its resultant narrower beamwidth, may also resolve your problem, especially if the interfering transmitter is close to your intended transmitter. Off-aligning your antenna, to place the offending transmitter's signal in the notch between the main beam and an adjacent side lobe of your antenna, may attenuate the interfering signal enough to allow good availability of your signal. Relocation of your antenna to block the path to the interference source, while maintaining an unobstructed path to your far-end transmitter, may be necessary. In any case, remember to collect and save your measured interference baseline data for future reference.

Note: When making the C/I or carrier-to-interference measurements of a system, you must use the actual system antennas–or an equivalent antenna mounted directly above your system antenna, and perfectly aligned on the desired receive signal. This is so that the data you measure represent exactly what the victim receiver is coping with. An omni-directional antenna is good for a quick snapshot of RF interference at a given site, but is not useful for C/I measurements, unless the system uses the same omni-directional antenna.

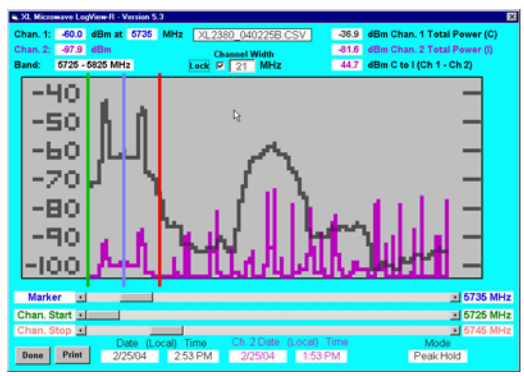
Carrier Power Measurement (remote radio on). Once an interference sweep has been accomplished, the remote transmitter is turned on. Using the victim receiver's intended antenna and a Spectrum Analyzer, make a Carrier sweep measurement at the site. If your system does not employ *Time Division Duplex (TDD) technology*, the use of Average mode is appropriate, as the signal is always present and its full signature will be captured by the analyzer sweep.



If your system utilizes TDD, the use of Peak Hold mode may be required in order to capture the full signature of your received signal due to its intermittent nature.

Examination of the RF Signature can reveal not only its received signal level, but the presence of signal distortion due to multi-path reflection or equipment problems. Notches or ripples in the signature are generally an indication of multi-path reflection or a high antenna system VSWR, and an asymmetrical RF signature usually an indication of an antenna or equipment issue.

Calculating the C to I Figure. Armed with the sweep of interference and the radio's carrier sweep information, you can now do a Carrier to Interference calculation. First, take all the power data points (in mW) within the passband of the carrier, e.g.: 30 MHz, 60 MHz, and so on–whatever the passband of the radio is. (Actually it is the radio's modulation passband, but it is commonly called the "carrier passband.") Then add the points together and convert this value to dBm. Perform the same operation to all of the interference-data points using these same passband frequencies. This will yield two dBm values, one for Total Carrier Channel Power and one for Total Interference Channel Power (normalized to the carrier passband). This is the best way of predicting whether you have sufficient *interference* fade margin for your victim receiver to provide you with a reliable link. The example above shows both the "carrier" and the interference traces superimposed on the same screen. The channel markers have been set to the radio's modulation bandwidth (20 MHz) and the auto calculation of the C/I figure is shown in the upper right of the display screen.



Note: When adding the individual data points across a channel, don't make the mistake of adding data points given in dBm. Adding logarithmic functions (dBm) is actually multiplying. If the data points are given as dBm, convert these log values (dBm) to linear values (mW); and then add the mW data points. Reconvert this linear answer to a log value, and you now have Total Channel Power expressed in dBm (the sum of all power data points within the channel or band of interest).

Manufacturers' Radio Types & Specifications. Various modulation/coding schemes are in use today. All these schemes attempt to improve throughput and security. And they are continually under development. The most common type of point-to-point radios generally don't have channels. Instead, they occupy a modulation passband of frequencies (e.g.: 2.5, 20, 40, 60, 85 MHz) centered on a specific frequency.

- FHSS. Frequency hopping spread spectrum radios change transmitter frequency rapidly within their band of operation. They cannot stay on any given hopping band for more than 400 ms, but they always transmit at full power. Their hopping bands are relatively narrow (typ. 1 MHz).
- DSSS. Direct Sequence Spread Spectrum (DSS) radios spread their energy over a wider bandwidth than hopping radios and therefore have a lower relative peak power at any given frequency (15 to 20 dB less). They operate by adding a pre-defined spreading code to the original signal.
- Threshold (Sensitivity). This figure is derived by transmitting a signal to the receiver, without any interference present, and slowly decreasing the transmit power until a BER of 1 in $1x10^6$ occurs. This level is the threshold specification of the transmitter.
- T/I. The Threshold-to-Interference (T/I) figure is sometimes given for specific radio models by the manufacturer. The T/I specification is determined by feeding a receiver a signal 1 dB above the receiver's specified threshold, then adding an interference signal and increasing its level until the receiver performance degrades to the stated threshold performance (typically a BER of 1 in $1x10^6$ for most digital receivers).
- C/N (S/N). The term Carrier-to-Noise (C/N) is synonymous with Signal-to-Noise(S/N), both terms referring to the ratio of the desired signal over thermal-noise—not an interfering signal (see Thermal Noise & Interfering Signals, discussed earlier).
- C/I. The Carrier-to-Interference (C/I) specification is available from the manufacturer. This specification is derived by first setting the transmitter to transmit a signal just under the receiver's overload point, free of interference. An interference signal is then added and increased until a BER of 1 in $1x10^6$ is produced. This is the receiver's C/I requirement and defines the minimum signal-to-interference ratio needed for reliable performance of the system.
- C/I Requirement. In order to reduce the C/I requirement, manufacturers employ varying modulation and coding schemes and error corrections: Reed-Solomon forward error coding, Viterbi convolutional decoding, Zempel-Liv data compression, and the like. In order to provide reliable service, various modulation/coding schemes require different C/I fade margins. Individual radio manufacturers usually identify this specification for their radios. Without specific information from the data sheet of the radio, the figures below will serve as a general benchmark since they are generally accepted as an industry standard, normalized to a BER of 1×10^{-6}:

Modulation used	Minimum C/I
QPSK (Quadrature Phase Shift Keying)	16 dB
16 QAM (4-bit Quadrature Amplitude Modulation)	24 dB
32 QAM	27 dB
64 QAM	30 dB
256 QAM	36 dB

Path Engineering Considerations. Following are some key points to address when designing and installing a reliable point-to-point link:

- Line-of-Site (clear path – 0.6 of the 1st Fresnel zone - *but not too high*!).
- Fade Margin (confirm the C/I figure at the site, using the system radios and antennas).
- Fresnel Zone Clearance. The primary component of path loss is the free-space signal loss from the transmitting antenna to the receiving antenna. But because of reflective planar surfaces such as water and pavement, or diffraction losses from intervening obstacles in the Fresnel zone such as buildings and mountain peaks, additional path loss may also result from multi-path reflections–sometimes called "Fresnel reflective loss." An infinite number of Fresnel zones appear coaxially around the center of the direct wave path from transmitter to receiver.

Each Fresnel zone boundary coincides with the point at which, if a signal reflection occurred, the reflected signal path would have a ½ wavelength relationship to the direct signal path. Each higher order Fresnel zone adds a ½ wavelength to the reflected path. Odd-order Fresnel zones (1, 3, 5…) reinforce the direct wave path; even-order Fresnel zones (2, 4, 6…) cancel the direct wave path. For reliability, point-to-point links are typically designed to have *0.6 of the first Fresnel zone clearance* (top, bottom, left, and right) from any obstruction. Anything less than 0.6 F1 results in additional diffraction losses. And anything more increases the chance of clearing an even-numbered Fresnel zone, and creating a multi-path reflection problem. Wavelength reference: a 2.4 GHz wavelength (□ is 12.50 cm (4.92 in.); a 5.25 GHz □ is 5.71 cm (2.25 in.); a 5.587 GHz □ is 5.11 cm (2.01 in.

- Earth Curvature. When determining if line-of-site exists (including Fresnel clearance), the earth's bulge should be considered. For paths under 10 miles, earth bulge is only a small consideration (approx 12.5 feet at the middle of the path). For longer paths, earth bulge should be adjusted for in path engineering calculations (eg 50 ft. @ 20 miles; 200 ft. @ 40 miles).
- Refraction. The earth's curvature, as well as atmospheric conditions (temperature, pressure, and water vapor) can refract or bend electromagnetic waves either up and away from or down and toward the surface of the earth. This bending can change frequently, hour to hour, day to night, season to season, and weather pattern to weather pattern. Refractivity is usually greatest near the earth's surface and becomes smaller the higher above the surface you go. To compensate for this effect, engineers use a refractivity gradient, or K factor, when designing point-to-point communication links. The K factor is the ratio of the effective Earth radius to the actual Earth radius. A K factor of 1 indicates no bending of the signal; a K factor of less than 1 means the electromagnetic wave is bent up, away from the surface. A K factor greater than 1 indicates a slight bending downward, towards the earth. The K factor value commonly used for microwave links is 1.333 (4/3) for normal atmospheric conditions, which means that *the radio horizon is farther away than the visual horizon.*
- Atmospheric Considerations. Climate affects path attenuation. A humid climate produces more path attenuation than a dry climate. In addition, weather and multi-path can have the effect of de-polarizing an RF link (the plane over which RF propagates–horizontal, vertical, circular). Shorter links are less affected by atmospherics than long links.

Link Reliability (availability). The predicted amount of time the system will be operating without error (BER <1 in $1x10^6$) is often expressed in "X number of nines." eg:

3 nines = 99.9% = 525.6 min/yr outage
4 nines = 99.99% = 52.56 min/yr outage
5 nines = 99.999% = 5.26 minutes per year outage (traditional TelCo std. for microwave links)
6 nines = 99.9999% = 31.5 sec/yr outage

Mitigation of Interference. Here is a checklist of some precautions an operator should take to mitigate system problems caused by either RF interference or path-induced problems.

- Optimize antenna locations or change channels/frequencies.
- Optimize antenna polarization horizontal/vertical.
- Off-align an RF interfering source into a notch between main and side lobes or change height of antenna.
- Resolve excessive antenna height. Go only as high as required to give you 0.6 clearance of the first Fresnel zone above all obstacles.
- Use a larger antenna. Larger antennas have more gain, narrower beamwidth, and better side lobe suppression.
- Re-route the link (move antenna location or use a repeater).
- Increase transmitter power, if allowed.

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Conclusion. It is extremely important for anyone deploying unlicensed band systems to minimize potential interference problems through proper system design, careful antenna placement, and avoidance of excessive antenna height. The information gained from a thorough site analysis with an appropriate spectrum analyzer can be used to determine optimum site locations; equipment required; carrier frequency; antenna type, height, and polarization; need for diversity antennas; and the like. The time invested in a thorough site analysis will greatly improve your chances of having a predictable and reliable link on the initial installation. With already installed systems, a site analysis will help determine the best way to mitigate interference problems and insure that the system provides reliable service.

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Analyze-R™ Model 2261A Spectrum Monitor / Analyzer

with Unattended Data Recording & Automatic C/I Calculation and 'Total Channel Power' option on the display