6. BANDWIDTH LIMITED MEASUREMENTS OF ULTRAWIDEBAND DEVICE EMISSIONS

Frank Sanders[1]

6.1 Introduction

In many cases, the characteristics of UWB signals must be measured using equipment that is bandwidth limited. I.e., the measurement bandwidth is less than the UWB emission bandwidth. Bandwidth limited measurements are necessary for at least three reasons:

- Coupling between UWB emissions and various types of radio receiver equipment will generally be bandwidth limited (by either the receiver RF front-end or the receiver IF section). Bandwidth limited measurements closely match the case of bandwidth limited coupling into receivers.

- Regulatory standards may be specified in particular bandwidths. Compliance measurements must be performed in (or extrapolated to) the required bandwidths.

- Adequate full-bandwidth measurement systems are not likely to be available to all measurement facilities. Even if such equipment is available, the outputs generated may not be satisfactory for all measurement purposes.

In this section, measurement techniques are described that may be generally applied with commercial, off-the-shelf (COTS) equipment.[2] COTS-compatible methods are included for measuring the following UWB emission parameters:

- emission spectra as a function of IF measurement bandwidth,
- pulse width estimation,
- pulse shape as a function of IF measurement bandwidth,
- pulse repetition rates, sequences, and gating,
- amplitude probability distributions as a function of IF measurement bandwidth,
- peak power,
- average power.

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[1]The author is with the Institute for Telecommunication Sciences, National Telecommunications and Information Administration, U.S. Department of Commerce, Boulder, CO 80305.

[2]COTS equipment is defined as measurement devices that are commercially available.

This section provides guidance for other laboratories in the implementation of UWB emission measurement techniques. Each technique is described both generically and as performed specifically at ITS using COTS equipment.[3] Based upon experience gained at the ITS laboratory, the technical strengths and weaknesses of each approach are described. Particular problems that other laboratories may encounter with these techniques are noted, along with any practicable solutions developed by ITS measurement personnel.

6.2 Bandwidth Limited Measurement Theory

A measurement result is the convolution of an input signal with the impulse response of the measurement device in the appropriate domain (e.g., time or frequency). The convolution width of a measurement device's impulse response may be wider than, equal to, or narrower than the input signal function. For UWB device emissions, the measurement convolution width is generally narrower than the device emission.[4] However, there may exist within the UWB emission some features that are individually narrower than the measurement convolution. These and other characteristics of UWB emissions must be taken into account in emission measurements, as described below.

6.2.1 Bandwidth Limited Time Domain Measurement Theory[5]

The convolution bandwidth of a time domain measurement may be limited by either the RF front-end or the time domain digitizer. If the RF front-end is an instrument such as a spectrum analyzer, then it will be the limiting factor. If the front-end is a wideband detector diode (typically a discrete component with 18 GHz bandwidth), then the digitizer will limit. In either case, the measurement system response will show time domain features that are limited by the fastest response of the slowest component. That is, a 500-MHz single-shot digitizer (with a wideband detector) will produce pulse widths that are no shorter than 2 ns. Given the emission characteristics of UWB devices examined in this study, this may be inadequate for accurate

[3]Unless otherwise noted, all measurement techniques described in this section have been implemented by ITS and have been used to generate the data that appear in Section 8 and Appendix D.

[4]Emission width may be defined at the 3 dB, 6 dB, 10 dB, 20 dB points, etc., in the appropriate domain.

[5]This discussion of time domain measurements assumes that the UWB RF emission is rectified by a diode or equivalent detector, either as a discrete component or as part of a system such as a spectrum analyzer. For other types of time domain measurements, including those that preserve phase information, see Section 5 of this report.

measurements of UWB pulse widths. But it will probably be more than adequate for measurements of pulse repetition rate, pulse sequences, and gating behavior. It will also be adequate for measurements of pulse-to-pulse dither intervals.

It is possible to utilize a wideband time domain measurement system to digitize a pulse (preserving the phase information) and then transform the waveform into a wideband spectrum, using the Fourier transform, as described in Section 5. Such a spectrum may in turn be convolved with narrower IF bandwidths to replicate the spectrum envelope that would be measured in any arbitrarily chosen receiver IF. While this approach may be feasible for some UWB systems, pulse to pulse waveform variation may require repetitive sampling measurements to form a spectrum, and dithering may make repetitive sampling difficult or impossible. Dynamic range may also be limited for some pulse measurements.

6.2.2 Bandwidth Limited Frequency Domain Measurement Theory

The convolution of a frequency domain measurement may be limited by either the RF front-end or the IF bandwidth of the measurement device, assumed to be a spectrum analyzer. The IF bandwidth is normally the limiting factor.[6] For this discussion, the spectrum analyzer convolution function is assumed to be essentially the IF filter shape.

If the IF bandwidth curve is substantially narrower than the spectrum being measured, then the convolution of the two functions is nearly identical to the input spectrum function. In this case, the spectrum measurement is nearly identical to the spectrum function that was applied to the analyzer input.

The features visible in the measured spectrum will only be resolvable down to the IF filter width. Features narrower than the filter will convolve to yield merely the IF filter shape. To further resolve those features, narrower IF filtering must be used.

While narrower IF filtering provides better resolution on spectrum features, two drawbacks result. The first is true for all spectrum measurements, while the second will occur in particular cases. The first problem is that the measurement takes proportionally longer to complete as the IF is narrowed. A trade-off results between measurement time and amount of detail in the resulting spectrum measurement. Measurement efforts must balance these factors. In practice, the width of the IF filtering will often be determined by the need to resolve the spectrum with the same bandwidth as a particular type of potential victim receiver. For example, a 30 kHz bandwidth

[6] In exceptional cases, the RF front-end is narrower than the IF section; those analyzers can usually be retrofitted with wider bandwidth (essentially wide-open) front-ends. The result is that the spectrum analyzer bandwidth is still ultimately limited by the IF section.

may be selected in the spectrum analyzer to match as nearly as possible the 25 kHz bandwidth of some types of land mobile radio receivers.

The second problem is that the signal-to-noise ratio (SNR) of the measured signal can decrease in narrower IF bandwidths. This will occur if the noise power in the measurement system decreases more slowly in the IF bandwidth than the power coupled from the spectrum being measured. The result is decreased dynamic range in the measurement. For example, in a narrow IF bandwidth the spectrum might only be measured 20 dB down from the highest point, as compared to perhaps 35 dB down in a wider bandwidth.

To determine when dynamic range will decrease with narrow IF bandwidth, consider first the manner in which measurement system inherent thermal noise varies as a function of IF bandwidth. The noise power present is directly proportional to the IF bandwidth. Measured in decibels, the inherent noise power therefore varies as 10 log (IF bandwidth).

Likewise, if the measured spectrum is noise, or approximates noise characteristics, then the spectrum power convolved in the IF varies as $10\log_{10}$ (IF bandwidth). In this case, the SNR of the spectrum is constant with IF bandwidth, and the dynamic range of the measurement is unaffected by the choice of IF bandwidth. A drawback to a narrower IF bandwidth is the longer time required to complete the measurement.

If the measured spectrum is not noise-like, the convolved measured power may change at a rate that is faster than $10\log_{10}$ (IF bandwidth). This case occurs for spectra generated by pulsed transmitters. Consider the case in which pulse width is t, pulse repetition interval is T, and normalized voltage measured in a spectrum analyzer peak detector at the fundamental frequency is A. For such transmitters, the spectrum that contains most of the transmitted power consists of lines spaced (1/T) apart. The line power envelope is classically sinc^2, with the first two nulls occurring at ±(1/t) relative to the fundamental frequency and subsequent nulls occurring at intervals of (1/t).[7]

The power measured in a line at the fundamental frequency is

$$p_{line} = A^2 \tag{6.1}$$

and the line power in decibels is

$$P_{line} = 10\log_{10}(A^2) \quad . \tag{6.2}$$

[7]The sinc^2 spectrum is only dominant through the first few lobes; more extended portions of the spectrum are dominated by transient effects in the rising and falling edges of the pulses.

The average power is

$$p_{ave} = A^2 \left(\frac{t}{T} \right) \tag{6.3}$$

or, in decibels

$$P_{ave} = \left[10\log_{10}(A^2) - 10\log_{10}\left(\frac{t}{T} \right) \right] = \left[P_{line} - 10\log_{10}(duty\ cycle) \right] \quad , \tag{6.4}$$

where duty cycle = (t/T) .

For pulsed emissions, peak power is the rate at which energy is transmitted during each pulse. This is therefore a linear function of the ratio of the pulse width to the pulse repetition interval. Therefore, the peak power is related to the average power and the line power by the following relationship:

$$P_{peak} = \left[P_{ave} - 10\log_{10}(duty\ cycle) \right] = \left[P_{line} - 20\log_{10}(duty\ cycle) \right] \quad . \tag{6.5}$$

For n lines convolved within a measurement bandwidth, the measured peak power varies with n as

$$P_{peak} = 10\log_{10}(n \cdot A)^2 = 20\log_{10}(n) + P_{line} \quad . \tag{6.6}$$

Since the number of lines within the convolution bandwidth is proportional to the bandwidth, the peak power varies as $20\log_{10}$ of the measurement bandwidth for line spectra. Figures 6.1 and 6.2 illustrate the behavior of a line spectrum convolved with bandwidths that range from significantly less than the line spacing to significantly wider than the pulse width. For typical analogous UWB device emissions, note that the width of the central lobe corresponding to that in Figure 6.2 will be on the order of a gigahertz or more.

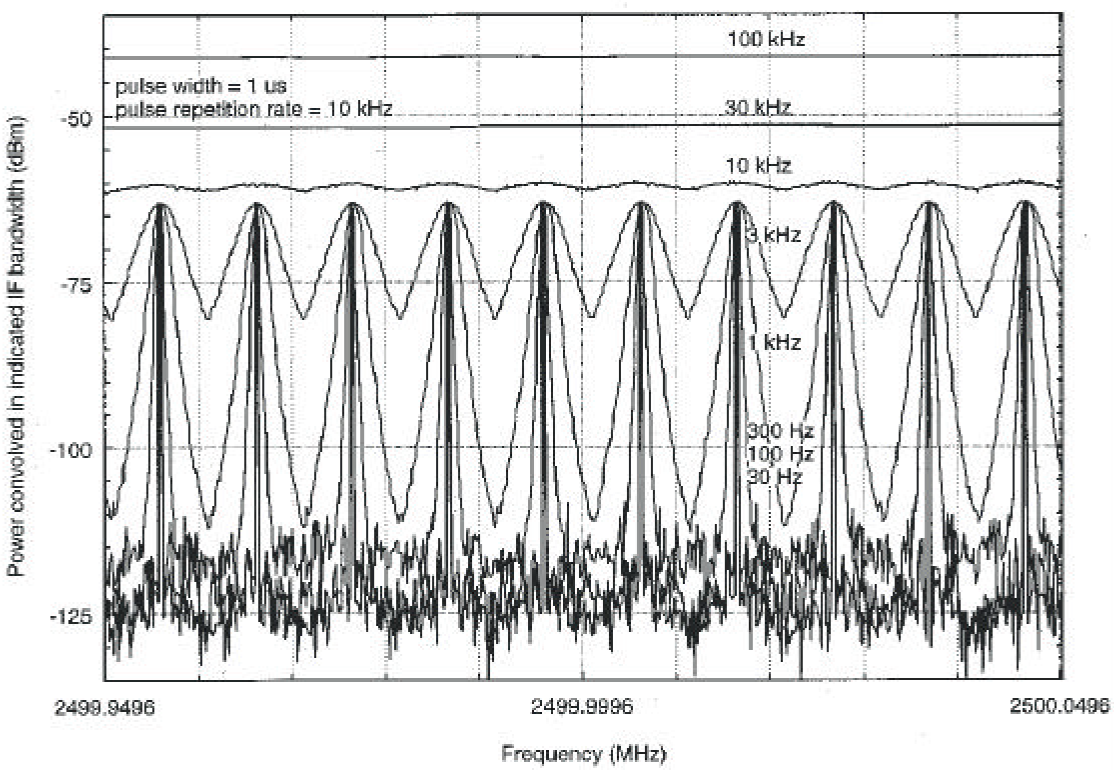

Figure 6.1. Detailed line spectrum measurement for a fixed-pulse-repetition rate transmitter. Pulse width is 1 µs and pulse repetition rate is 10 kHz (pulse repetition interval is 100 µs). Duty cycle is 10log(1/100) = -20 dB. Peak power from the transmitter is -20 dBm and RMS average power is -40 dBm. Measured line power is -60 dBm. Multiplying the power per line by the number of lines in the central lobe of the spectrum at the 3-dB points gives [(-60 dBm + 20 dB) = -40 dBm] for the computed average power, in agreement with the known average power. Note 20log(bandwidth) progression for measured power when convolution bandwidth exceeds the line spacing.

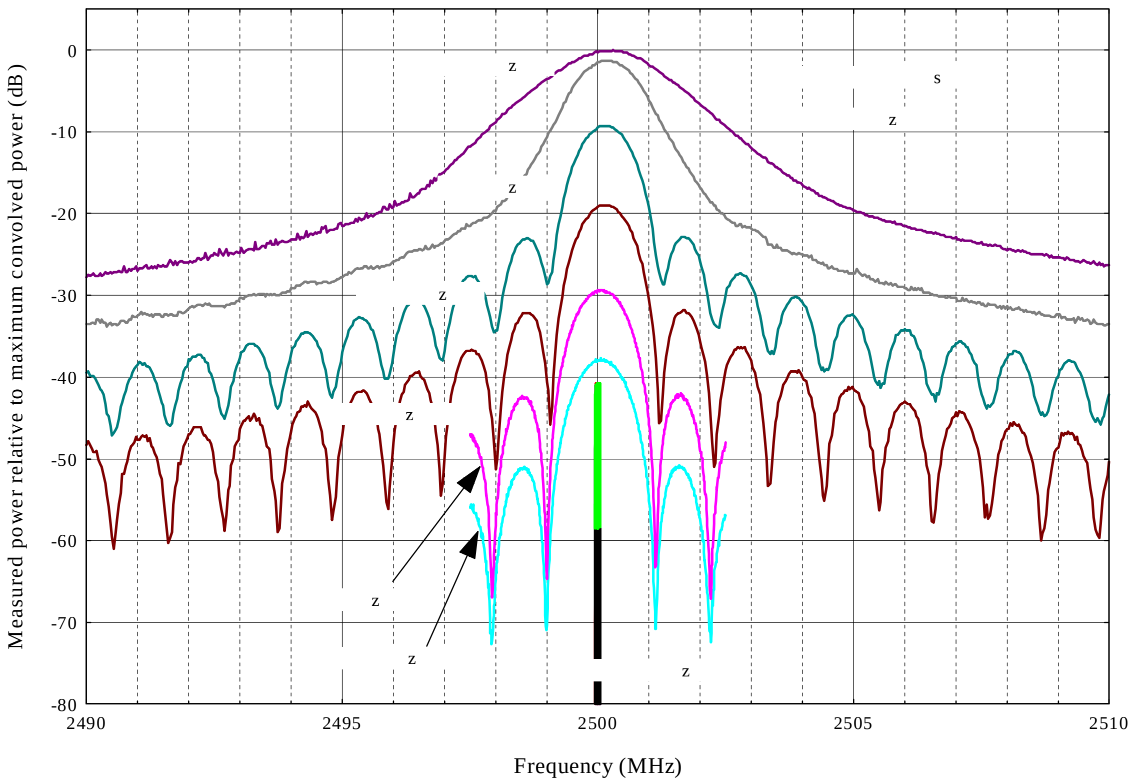

Figure 6.2. The spectrum of Fig. 6.1 is shown for wider measurement bandwidths. 20log(bandwidth) progression holds up to bandwidth of (1/pulse width)= 1 MHz. When bandwidth exceeds (1/pulse width), only a small additional percentage of power is convolved.

As long as measurement bandwidths are narrower than the convolved spectrum features, the measured emission envelopes of all peak-detected emission spectra will vary as a function of measurement bandwidth at a rate between $10\log_{10}$(bandwidth), as for noise, and $20\log_{10}$ (bandwidth), as for pulsed signals. Other signal modulations may produce rates intermediate between $10\log_{10}$ and $20\log_{10}$. UWB device emission levels may vary with bandwidth at such intermediate rates.

Measurements of UWB emissions will show the functional bandwidth dependence empirically. If the dependence is $10\log_{10}$ (the same as thermal noise in the measurement system), then the SNR and dynamic range of the measurement will be constant as a function of measurement bandwidth. If the UWB emission dependence is between $10\log_{10}$ and $20\log_{10}$ of measurement bandwidth, then SNR and dynamic range of a UWB spectrum will increase with increasing measurement bandwidth, until the measurement bandwidth equals the emission bandwidth of the UWB emitter. If measurement bandwidth exceeds the UWB emission bandwidth, the SNR and dynamic range will decrease, as the convolved power in the UWB spectrum will remain constant but the thermal noise convolved by the measurement system will increase at a $10\log_{10}$ rate.[8]

6.3 Measurement Approaches

The application of hardware and software to the task of characterizing UWB emissions is described below. Unless otherwise noted, the descriptions are taken directly from operational measurements performed on UWB devices at the ITS laboratory.[9]

6.3.1 COTS Hardware Requirements

The following types of equipment are generally required for UWB measurements:[10]

- spectrum analyzer with general purpose interface bus (GPIB) capability,
- digital oscilloscope with GPIB capability,
- RF front-end hardware such as low noise amplifiers, bandpass filters, and attenuators, packaged either as discrete components or within COTS RF front-end preselectors,[11]
- broadband antennas designed for electromagnetic interference (EMI) and electromagnetic compatibility (EMC) measurements, and

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[8]As the emission bandwidths of UWB devices are often in excess of a gigahertz, it may be assumed that a bandwidth limited measurement system will not have an IF bandwidth wide enough to completely convolve the UWB emission.

[9]The results of measurements performed with these procedures are reproduced in detail in Appendices A-E, and are summarized in Section 8 of this report.

[10]A vector signal analyzer (VSA) may be substituted for the spectrum analyzer and oscilloscope specified in this list. However, ITS has not yet performed UWB emissions with a VSA, and the ultimate feasibility of these measurements with a VSA has therefore not been determined by this laboratory.

[11]For example, this capability may be provided by an Agilent (formerly Hewlett-Packard) 85685A preselector. Other COTS RF front-ends are available from other manufacturers; the equipment described here is specified only for the purpose of explaining the type of capability that the RF front-end is expected to contain.

- laptop PC-compatible computer or equivalent that can be connected to a GPIB or equivalent interface for instrument control and data acquisition.[12]

6.3.2 Software Requirements

Some measurements that characterize UWB emissions, such as amplitude-probability distributions (APDs, described below), require the acquisition of thousands or millions of data points.[13] Such measurements are difficult or impossible to perform adequately[14] with systems that are manually controlled and operated. Raw measurement data may be so voluminous as to make analog recording techniques (e.g., pen-plotter outputs) impractical; some types of data analysis (e.g., APD generation from raw data) operate on data quantities that can only be reduced by computers. For these reasons, measurement laboratories engaged in UWB emission characterization should be equipped with a computer that can be used to control measurement instrumentation, acquire data through a widely available bus interface (e.g., GPIB), and analyze the resulting data.

Software to perform limited instrument control, data retrieval, and analysis will be necessary to complete the measurements and produce analyzed data sets. The software should perform the following functions:

- Set spectrum analyzer parameters, including center frequency and frequency span, IF bandwidth, video bandwidth, detector type, sweep time, attenuation, reference level, and number of points per data trace (if necessary);

- Set digital oscilloscope measurement parameters, including time base, voltage scale, coupling mode, and trigger mode;

- Command a specified number of data traces (e.g., 1000 traces) to be triggered on a spectrum analyzer; and

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[12]An example of this type of interface is the National Instruments GPIB-to-parallel interface adapter. Other types of GPIB adapters are available from other manufacturers; this device is specified only for the purpose of describing the type of capability required.

[13]Some spectrum analyzers with integrated APD capabilities are becoming available as of the release date of this report. These machines were not available for use by ITS when the report was written.

[14]An adequate measurement is defined to be efficient (requiring a minimum of operator time and knowledge to perform), repeatable, and automatically documented by the measurement system.

- Command a specified number of data traces to be taken on a digital oscilloscope;

- Record to selected media (hard disk, magneto-optical disk, etc.) all triggered data traces from a spectrum analyzer and a digital oscilloscope to the controlling computer. Each trace from the measurement instrument should be recorded as an individual data record; and

- Record critical supporting information with each data record. Such documentation might consist of instrument settings, date, time, and logistics information such as the name of the device being measured and the measurement engineer.

The software must support the following functions on recorded data:

- Add calibration factors to measured data values, if such corrections were not included in raw data (necessary corrections are described in detail below);

- Correct measured spectra for variable effective aperture of the measurement antenna, as described in Part 4 of Appendix C and (also below in this section);

- Retrieve individual data records (with corrections described above) for CRT screen display and printing (these should include spectrum measurements and time waveforms);

- Process hundreds or thousands of individual spectrum analyzer or oscilloscope data records into APDs, as described below (software should store generated APDs for later retrieval and printing). (Alternatively, some newly available spectrum analyzers incorporate integrated APD capabilities. See footnote 13.)

Commercially available measurement and data analysis software packages that perform every function described above probably are not available; however, some combination of commercially available packages may be adequate to perform the necessary functions.[15]

[15]At the ITS, the software used for these measurements was originally written to control a custom-designed NTIA measurement facility, the Radio Spectrum Measurement System (RSMS). As such, the RSMS software package is much more complex than is required for UWB device emission measurements.

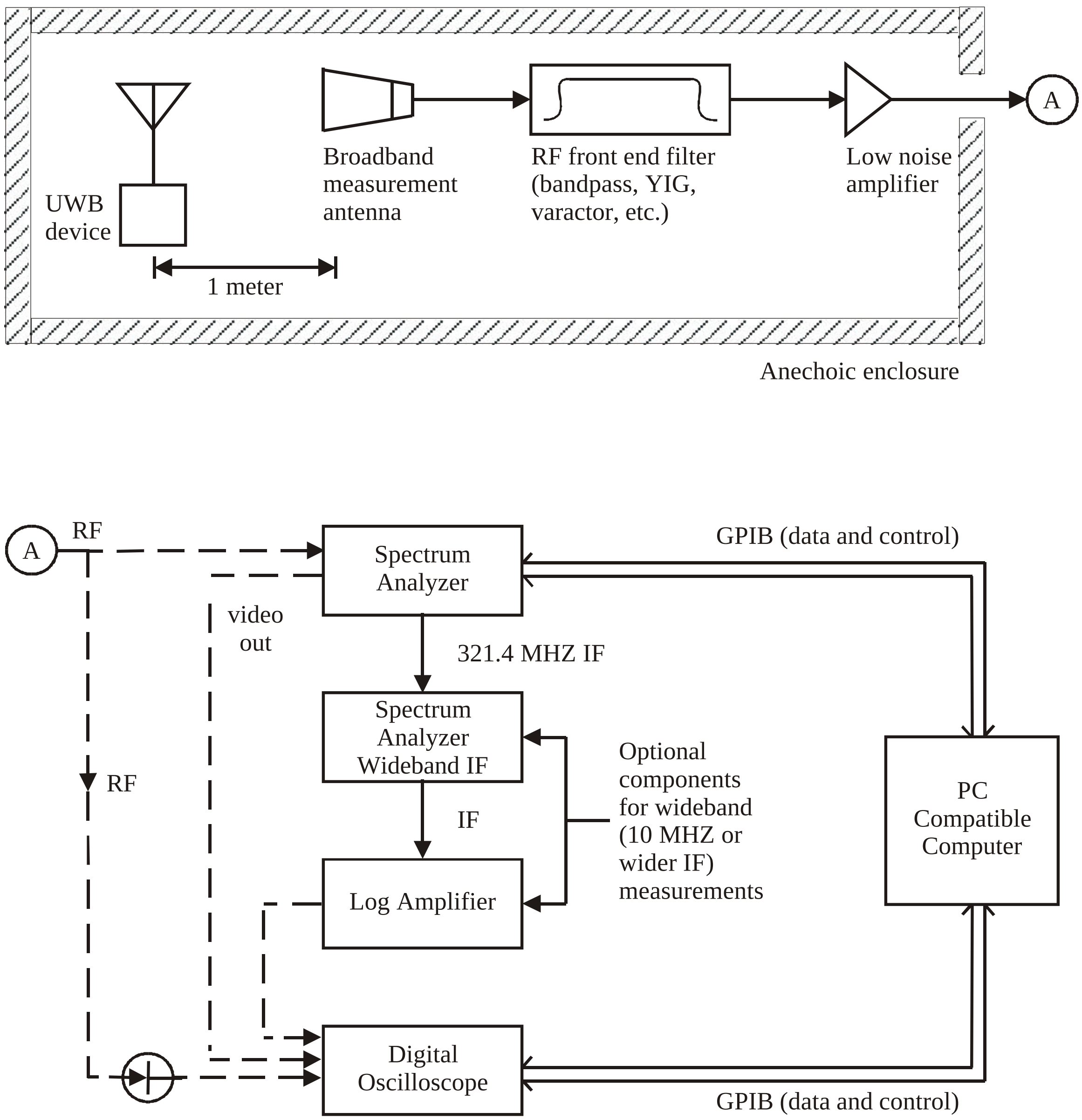

Figure 6.3. UWB emission measurement block diagram.

6.3.3 Generalized Measurement System

A generalized measurement system for characterization of UWB device emissions is shown in Figure 6.3. The components shown in the figure are described in detail below.

Measurement Environment. The UWB device should be placed in an environment where measurement system multipath and external radio signals are eliminated or minimized. The best possible choice is a high-performance anechoic chamber. For ITS measurements, no such facility could be scheduled for use within the time constraints of this project. Two alternative environments that were utilized during ITS measurements were a large room (measuring about 15 m by 15 m by 10 m high) with a metal ground plane, and a smaller laboratory room with a temporary enclosure built of stacked anechoic foam blocks. In the large room, UWB devices were mounted on Styrofoam blocks about 2.5 m above the ground plane; in the anechoic enclosure, UWB devices were mounted at a height of about 1 m above the floor.

Background signals may present a problem for UWB measurements not performed in an anechoic chamber. This problem is exacerbated by the emission bandwidths of UWB signals, which may in some cases occur in portions of the spectrum occupied by prominent background signals including UHF television (512-806 MHz); analog cellular and trunked mobile communications (806-902 MHz); pagers (928-932 MHz); PCS cellular communications (1.9 GHz); air route surveillance radars (1215-1400 MHz); and tactical air surveillance radars (2.7-3.7 GHz, and especially 2.7-2.9 GHz for airport surveillance radars). Signals from these sources may be attenuated somewhat by the walls of the laboratory, and may be further reduced within an anechoic foam enclosure. But measurements of background levels should be performed prior to UWB device emission measurements, and can subsequently be subtracted from the measured UWB spectra to yield the UWB spectra alone.

Measurement Antenna. Measurement antennas must have a sufficiently wide frequency response. This may be a non-trivial problem for UWB device emissions. UWB measurements by ITS have typically spanned such frequency ranges as 600 MHz to 6 GHz, a full octave. Multiple antennas may be required if the frequency range to be measured is not completely included by a single antenna.[16] Commercially available wideband horn antennas have performed well for all ITS and some National Institute of Standards & Technology (NIST) measurements described in this report. If the measurement antenna polarization is linear, the antenna orientation needs to be matched to the polarization orientation of the device being measured. This is accomplished by rotating the measurement antenna until the received power level is maximized.

Because UWB device emissions may be relatively low-amplitude, the measurement antenna will usually be placed as close as practicable to the device. The ITS measurements performed in the course of this project utilized an antenna at a distance of 1 m from the devices being measured.[17]

The measurement antenna must be calibrated for the distance at which measurements are performed. Again, wideband horn antennas have proven to be workable in this respect, as they

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[16]Some commercially available antennas may perform adequately at frequencies beyond their nominal specifications. Such performance extensions can be determined at a qualified antenna test facility.

[17]The antenna must be located in the far field of the device being measured.

typically can be acquired with calibration curves made at 1 m. If the measurement antenna does not have a constant effective aperture (i.e., if the antenna gain does not increase as $20\log_{10}$ [measurement frequency]), the resulting spectra must be corrected to the constant effective aperture case. Section C.4 of Appendix C describes the necessary spectrum corrections for non-constant effective aperture measurement antennas.

RF Front-end. Because UWB device emissions are often too weak to overdrive the noise figure of spectrum analyzers, a low-noise amplifier may be required at the output of the measurement receiver antenna. All devices measured by ITS for this report required such front-end preamplification. In an optimized measurement system, the sum of the preamplifier gain and preamplifier noise figure should be nearly equal to the noise figure of the spectrum analyzer across the frequency range to be measured.[18]

Although UWB device emissions may have low amplitude within the convolution bandwidth of the measurement system, the total power convolved by the front-end preamplifier may be high enough to cause overload of that component. The preamplifier may also experience overload due to ambient signals if the measurements are not being performed in an anechoic chamber. Overload conditions must be checked by measurement personnel.[19] If overload is experienced, then appropriate RF filtering will be required between the antenna and the preamplifier.

Spectrum Analyzer. A spectrum analyzer may be used to measure both the bandwidth limited spectra and time domain information (when operated in zero hertz span). Spectrum analyzers typically have noise figures of 25 dB or more at frequencies below 2.5 GHz, and noise figures increase with frequency due to mixer noise, typically at a rate of about 5 dB per mixing stage.[20] As noted above, the preamplifier noise figure and gain should be optimized to work with this noise figure.

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[18]Higher noise figure results in loss of sensitivity; gain that is too low will fail to overdrive measurement system noise, while gain that is too high will reduce available dynamic range. But since UWB emission measurements typically observe low-amplitude signals, dynamic range is not likely to be an important problem for these measurements.

[19]Overload may be checked by inserting attenuation between the antenna and the preamplifier and observing a corresponding drop in signal level at the spectrum analyzer output. If the drop is less than the attenuator value, then feed-through directly into the preamplifier or the spectrum analyzer may be occurring, or the preamplifier may be in an overload condition.

[20]Spectrum analyzer noise figure at a given frequency may be checked by terminating the input, setting RF attenuation to zero, IF bandwidth to 1 MHz, video bandwidth to 1 kHz, and detector to sample. The difference between the measured noise level and -114 dBm is the analyzer noise figure at that frequency.

Detector and Oscilloscope. Time domain measurements at bandwidths wider than those available in the spectrum analyzer are performed with a diode detector and an oscilloscope, as shown in Figure 6.3. For these measurements, the RF line is disconnected from the spectrum analyzer and is routed through the diode to the oscilloscope. Note that the bandwidth limited video output from a spectrum analyzer can also be routed to the oscilloscope, omitting the detector.

Optional Measurement Hardware for Bandwidths Wider than Nominal Spectrum Analyzer IF. For the ITS measurements, a commercially available wideband IF module was procured for one of the spectrum analyzers. This module was specified with performance to 100 MHz bandwidth, but the spectrum analyzer RF front-end was only 22 MHz wide, thus limiting the overall performance to a maximum of 22 MHz.[21] Because the wideband IF section did not include a detector, ITS measurements utilized a wideband log amplifier/detector at that module's output. The log detector output was connected to the oscilloscope input. Calibration was performed manually for this project, although software will be required in the long term.

6.3.4 Calibration

Measurement devices must be individually calibrated by certified facilities. But additional calibrations and corresponding corrections may be expected to be necessary for the complete UWB measurement system. These include:

Corrections for Non-constant Effective Aperture Measurement Antenna, and Conversion to Incident Field Strength. As described in Section C.4 of Appendix C, the measured spectra must be corrected for non-constant aperture of the measurement antenna. This correction is also required if the measured spectra are to be easily converted to incident field strength. Conversions between measured power in a circuit and incident field strength are derived in Section C.1 - C.3 of Appendix C.

RF Front-end. The frequency-dependent gain of the RF front-end (including the loss through the front-end filtering, if any, and the RF line from the preamplifier to the spectrum analyzer) must be subtracted from the power values measured at the spectrum analyzer. ITS generally uses a Y-factor noise diode calibration procedure for this purpose. Signal generators may also be used.

Special Wideband IF Unit and Discrete Wideband Log Amplifier/Detector, if Used. The wideband IF unit used by ITS for some measurements required provision for an IF gain factor within that unit. The response of the discrete log amplifier/detector between the wideband IF and the oscilloscope must also be calibrated, if these devices are used in the measurement system (Figure 6.3).

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[21]The IF was used at 10 MHz and 20 MHz for the ITS measurements.

6.4 Types of UWB Measurements

6.4.1 Spectrum Measurements

Spectrum analyzer RF front-ends are sometimes on the order of two to three gigahertz wide for tuned RF frequencies below about three gigahertz.[22] At higher frequencies, such analyzers may incorporate a tunable RF bandpass filter which may be approximately 20 MHz wide. Some spectrum analyzers may be used in combination with external preselectors. These preselectors typically utilize varactor filters at frequencies below 500 MHz and yttrium-iron-garnet (YIG) filters at higher frequencies. The bandwidths of these preselector stages may be expected to be between 15 MHz and 35 MHz. If the ultimate bandwidth limit is in the IF section, then the widest bandwidths available will most often be between 3 MHz and 10 MHz. In exceptional cases, spectrum analyzer IF sections may be procured that are as wide as 100 MHz (as in Figure 6.3).

Spectrum Envelope Measurements. ITS spectrum analyzer measurements of UWB emissions were found to be most efficiently performed with the following spectrum analyzer settings: Swept-frequency mode, zero front-end RF attenuation, reference level chosen as appropriate for the UWB emission levels, positive peak detection, maximum-hold trace mode, video bandwidth at maximum, and IF bandwidth selected progressively from the widest available bandwidth (3 MHz) to a much narrower setting (10 kHz, for approximation of land mobile radio bandwidths).

Swept-frequency measurements have been found to be fast and practical for UWB device emissions in this project. Only at bandwidths narrower than about 30 kHz does the sweep time exceed a few seconds across the requisite several gigahertz of spectrum. For some spectrum analyzers, it may be impossible to perform a single sweep across the entire range of interest (e.g., 800 MHz to 6 GHz). In those cases, the spectrum is swept in two or more measurements (e.g., 800 MHz to 2.5 GHz, and then 2.5 GHz to 6 GHz). Automation of these measurements by ITS has increased the speed and reliability of the UWB measurement project and its results.

For spectrum measurements in IF bandwidths greater than the widest available in a conventional spectrum analyzer (e.g., wider than 3 MHz or 10 MHz, depending upon spectrum analyzer model), an optional wideband IF module and log amplifier/detector (or other circuitry with equivalent operational capability) will be required, as shown in Figure 6.3. The wide-bandwidth measurement is performed as follows: The spectrum analyzer is tuned to the first frequency to be measured in the spectrum, in a zero hertz span. A single oscilloscope trace is acquired through the wideband IF and the log amplifier, as shown in Figure 6.3. The oscilloscope sweep time must be long enough to ensure that a maximum-power pulse from the UWB device is recorded

[22] This is the case, for example, for some spectrum analyzers which couple input signals at frequencies below two or three gigahertz directly into a mixer downconverter.

somewhere on the trace. After the oscilloscope trace is recorded, the spectrum analyzer is tuned (still in a zero hertz span) to a second frequency. The second frequency should be as close as practicable to the first frequency plus the IF bandwidth. For example, if the first frequency is 800 MHz and the IF bandwidth is 20 MHz, then the second frequency is 820 MHz. The measurement is repeated, with a data trace recorded as before. This process continues until the entire spectrum has been measured. For the example given here, if the spectrum to be measured is 800 MHz to 6 GHz, then the set of frequency steps at which measurements will be recorded from the oscilloscope will be 800 MHz, 820 MHz, 840 MHz, etc., to 6 GHz. For the hypothetical case described here, the measurement would require the acquisition of 260 oscilloscope traces; therefore, this process is most efficiently and reliably performed with an automated (software-controlled) data collection system.

To generate the spectrum in the wide IF bandwidth, each oscilloscope trace must be retrieved from storage, the maximum (peak-voltage) point on each trace must be determined, and those voltages must be converted to power values in the measurement circuit. This is done by making use of the log amplifier/detector calibration that was performed earlier. The final spectrum for the example considered here would consist of 260 data points. The process of retrieving thousands of raw data points, selecting the 260 maximum amplitude points from each trace, converting those points to power in the measurement circuit, and plotting the points as a spectrum requires software.

Bandwidth-dependence Measurements. As noted in 6.2.2 (above), measured emission amplitudes from UWB devices vary as a function of measurement bandwidth. This variation represents the relative levels that are coupled into receivers that are bandwidth limited. For purposes of EMC/EMI characterization, and possibly also for regulatory and statutory purposes, it is therefore necessary to understand the rate of the progression for extrapolation to arbitrarily specified receiver bandwidths. Determination of this bandwidth dependence may be performed in two ways. The first is to measure the entire spectrum (as above) in at least several bandwidths, and note the progression between one spectrum and the next. The second method, which can be performed at specific frequencies of particular interest (e.g., a global positioning system satellite frequency at 1575 MHz) may be performed as follows:

Place the spectrum analyzer in a zero hertz span mode at the frequency of interest. Set the detector to positive peak and the attenuation to zero. Set the video and IF bandwidths to their widest possible values. Set the sweep mode to “single” (i.e., so that only one sweep will be acquired when the proper trigger button on the analyzer is pushed). Set the sweep time to 60 seconds. With the UWB device emissions in progress, start the single sweep. At intervals of 6 seconds, reduce the IF bandwidth in a 1, 3, 10 progression or some approximate equivalent. The result will be a stair-step trace as shown in Figure 6.4. This progression is a direct indication of the relative peak-detected coupling at IF bandwidths of 3 MHz, 1 MHz, 300 kHz, etc., down to 100 Hz.

Depending upon the transmitter characteristics, it has been observed that the bandwidth progression is not necessarily constant from one step to the next, as seen in Figure 6.4. Such non-uniformity is documented by this measurement technique. At wider bandwidths, the progression indicates extrapolated levels for bandwidths wider than those that can be directly measured (e.g., 50 MHz). The method of extrapolation is described in Section 8 of this report.

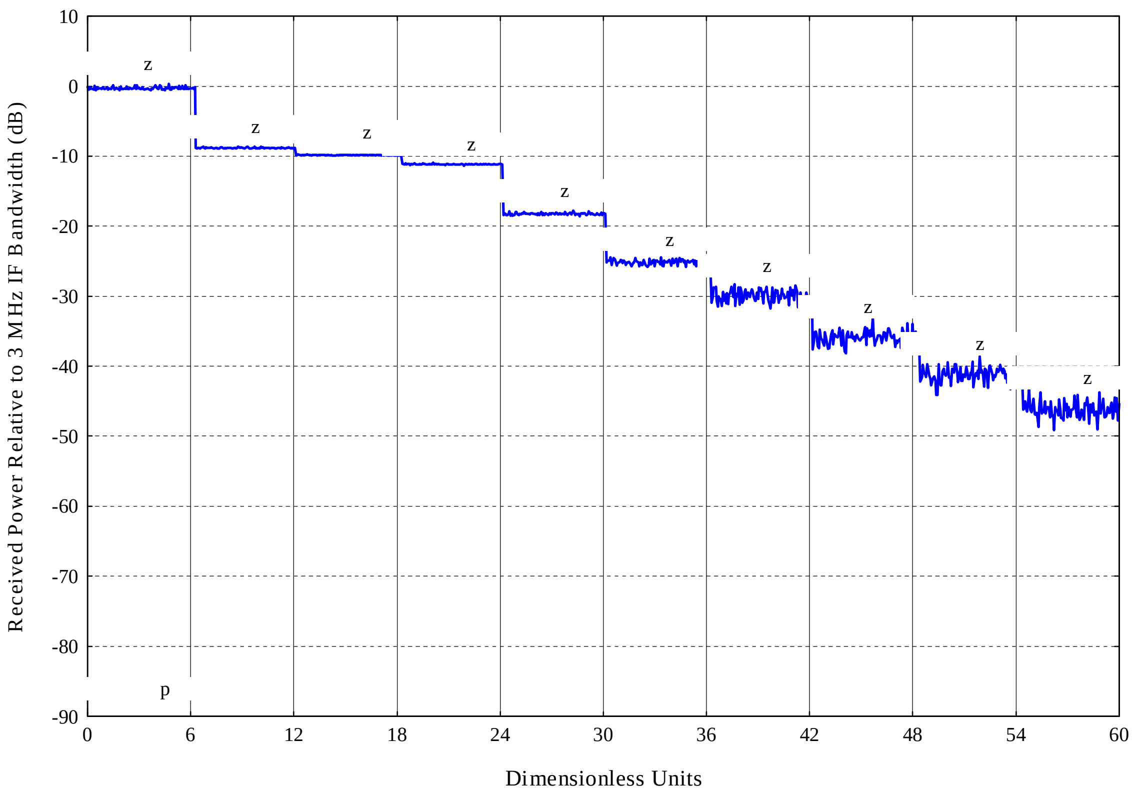

Figure 6.4. Bandwidth progression measurement example for a UWB signal. The emission is a pulse sequence (2 MHz pulse repetition rate) that dithers about 1% of the nominal pulse repetition interval on a relative (pulse-to-pulse) time base. The variable-rate progression demonstrates the usefulness of empirical data for determination of coupled UWB peak power as a function of receiver bandwidth.

6.4.2 Amplitude Probability Distribution Measurements

Amplitude probability distribution (APD) measurements show the percentage of time[23] that emissions from a device exceed a given power threshold. APD plots are typically produced on Rayleigh scales, as shown in Figure 6.5. APDs have been a critically important tool for the ITS characterization of UWB emissions. An APD curve will show the entire time-occupancy distribution at a frequency and in a selected bandwidth. It may be processed to show peak level in the bandwidth and several averages, including root-mean-square (RMS) (that is, linear average power), average voltage, and log average. APDs are discussed in more detail in Appendix A.

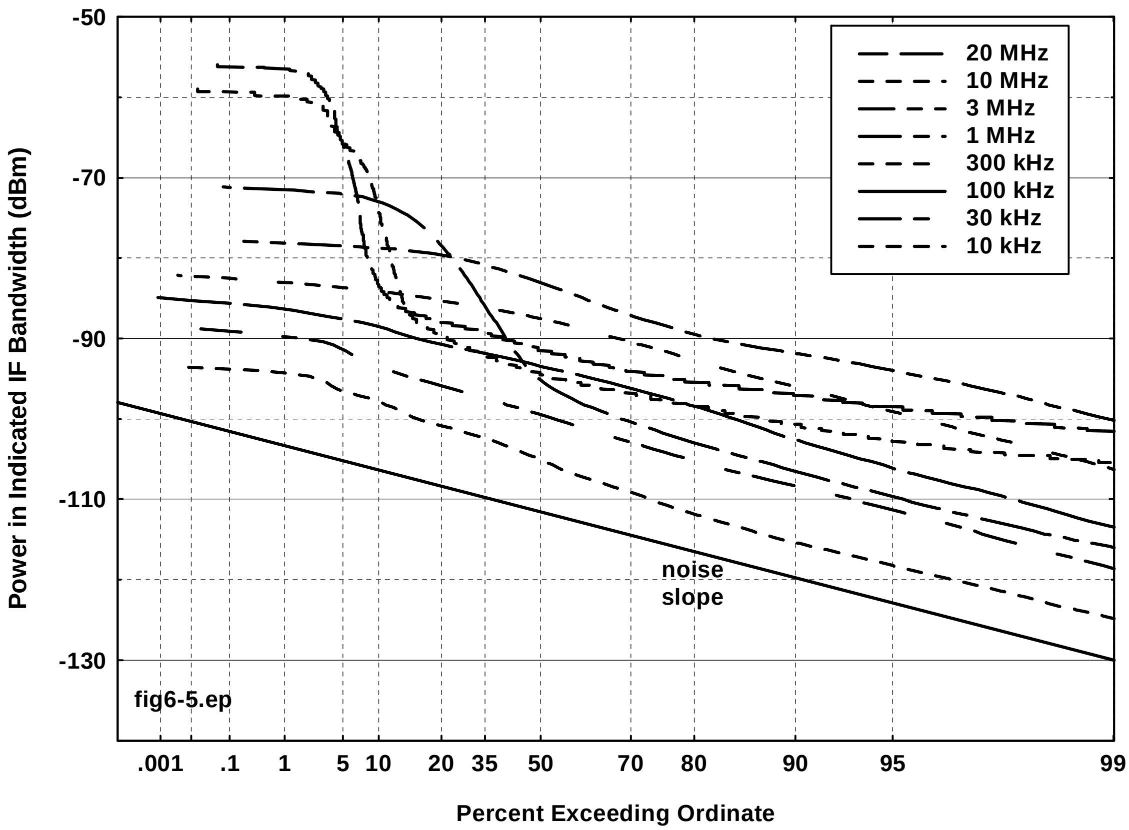

Figure 6.5. APD measurement example. The data for bandwidths of 10 kHz to 3 MHz were acquired with a spectrum analyzer. The data in 10 MHz and 20 MHz bandwidths were acquired with a commercially available wideband IF spectrum analyzer, detected with an external log amplifier, and recorded from a digital oscilloscope. Refer to Figure 6.3 for measurement system block diagram.

[23]Actually, percentage of samples, but if the sampling is not correlated with the device emissions, this becomes equivalent to percentage of time.

APD measurements require that power level in the UWB device emission be sampled as a function of time at the desired frequency and bandwidth. The time sampling may be performed with either a spectrum analyzer or a digital oscilloscope.[24] For either approach, the APD measurement will require automation of at least some portions of the measurement system.

APD Sampling with a Spectrum Analyzer. Unless a spectrum analyzer incorporates an integrated APD capability (see footnote 13), APD sampling is performed as follows: The spectrum analyzer is tuned in a zero hertz span to the desired frequency. Attenuation is set to zero, and reference level is set to a value that is about 10 dB above the maximum UWB emission amplitude. The spectrum analyzer video bandwidth is set to the widest possible value. Sample detection is selected.[25] The IF bandwidth is selected as required for the APD curve (in these measurements, values between 10 kHz to 20 MHz were used). Sweep time is unimportant, with the caveat that it must not be synchronized with the UWB device operation in any way.

With the UWB device in operation, a sweep is taken, and the data trace that results is stored electronically for future retrieval. This process is repeated until an adequate number of samples have been collected. If 1,000 points are generated within each spectrum analyzer sweep, then 100 sweeps will collect 100,000 points. It has been determined that between 100,000 and 1,000,000 points are required for adequate APD data on a variety of UWB transmitters. In the experience of ITS on this project, the measurement system needs to be automated for the generation and acquisition of the corresponding number of sweeps (between 100 to 1,000) if the measurements are to be performed efficiently and reliably.

Because APD measurements do not reconstruct waveforms, APD sampling rates are not constrained by the classical Nyquist rate of (2 x sampling bandwidth). Slower sampling is permitted under the condition that the samples are statistically uncorrelated with UWB device

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[24] APD sampling may also be performed directly with some newly available spectrum analyzers. Vector signal analyzers may also be feasible, but ITS has not tried a VSA to date.

[25] In the course of this project, it was observed that the sample detector bandwidths of some spectrum analyzer models are narrower than the widest IF bandwidths in the same analyzers. This problem can be checked as follows: Terminate the spectrum analyzer input, set the frequency span to zero Hz, and set the tuned frequency to any value (e.g., 1 GHz). Select the widest IF bandwidth with positive peak detection and maximum-hold trace mode. Allow the trace to build to a maximum. Retain the resulting trace on the analyzer display. Select a second trace, and change to sample detector mode. Select maximum-hold trace mode and allow the resulting trace to build to a maximum. If the maximum-hold sample detector trace does not eventually build to the same level as the maximum-hold positive peak detector trace, contact the spectrum analyzer manufacturer.

operations (e.g., the UWB pulse gating interval should not be synchronized with measurement equipment sampling).

APD Sampling with an Oscilloscope. An oscilloscope may be required for the collection of data samples at IF bandwidths exceeding the maximum available in conventional spectrum analyzer IFs. The ITS system, for example, utilized a specially procured (but commercially available) wideband IF unit that is housed in a spectrum analyzer chassis but that does not incorporate the spectrum analyzer detector functions (Figure 6.3). An external, discrete wideband log amplifier/detector was used to send 10 MHz and 20 MHz IF data to a digital oscilloscope. The oscilloscope was used to collect APD data in the same manner as the spectrum analyzer. The oscilloscope must not be set in an envelope-detection or peak-detection mode or some other mode that biases the samples toward higher values. Oscilloscope data traces are recorded electronically for later retrieval and analysis. As for the spectrum analyzer, this is best accomplished with software-automated data collection routines.

APD Data Analysis. APD raw data must be converted into finished APD curves. Unless a spectrum analyzer contains an integrated APD capability (see footnote 13), there is no practicable way to do this without software. APDs may be generated by separating the points into predetermined bin sizes (thus reducing the size of the finished file), or by accumulating all of the 100,000 or 1,000,000 points into a statistically indexed array (resulting in a larger final APD file size). The APD curve is conventionally graphed on a Rayleigh plot,[26] as shown in Figure 6.5.

APD curves may be further analyzed to determine the following critical emission parameters at the measured frequency in the measured bandwidth: peak power, RMS average, average voltage, and log average. ITS engineers have found APD curves to be useful in part because of the amount of information that can be directly determined from them.

6.4.3 Pulse Width and Shape Measurements

Pulse Width. Detailed pulse width measurements require the use of a measurement systems such as those described in Section 5. But COTS equipment may be used to estimate pulse width. Two methods are available. The first is to measure the width of the UWB spectrum at 10 dB or 20 dB points.[27] The inverse is approximately equal to pulse width. This is only an approximate measure

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[26]The Rayleigh plot shows decibel power on the ordinate vs. $10\log_{10}$ [-ln(% samples/100)] for samples exceeding the ordinate power.

[27]UWB spectrum measurements performed in this project did not generally result in clearly defined 3-dB bandwidths. Sometimes 10 dB was difficult to define; 20-dB points were generally definable.

of emitted pulse width, and includes the effects of final-stage UWB RF components such as output bandpass filters and the radiating antenna.

The second pulse width measurement method is to send the output of the measurement system to a discrete-component wideband diode detector, and connect the detector output to an oscilloscope. The oscilloscope may be used to estimate pulse width down to at least the inverse of the maximum oscilloscope bandwidth in single-shot (as opposed to repetitive sampling) mode. For a 50 MHz bandwidth, for example, pulse width may be estimated down to 20 ns. A scope that operates at 1 GHz bandwidth without repetitive sampling may be adequate to measure pulse widths down to about 1 ns. If scope bandwidth in single-shot mode is inadequate for measurement of a UWB pulse width, then the first method (estimating pulse width from spectrum width) may be the only available alternative.

Pulse Shape as a Function of Receiver Bandwidth. For purposes of EMI/EMC evaluation with various receiver types, the shape of the pulse should be measured through a spectrum analyzer in a variety of IF bandwidths. The pulse shapes are recorded in a range of bandwidths (e.g., 10 kHz to 20 MHz) for future reference in studies of compatibility with receivers having corresponding IF bandwidths. (This assumes that the pulse shapes so measured are determined by the impulse response of the receiver IF section.)

6.4.4 Pulse Repetition Rate, Dither Sequence, and Gating Measurements

In order to measure nominal repetition rates, dither sequences, and gating, pulse sequences must be measured. These have been found to be most easily measurable with the RF from the UWB transmitter connected to a wideband discrete-component diode detector. The diode output is connected to an oscilloscope and the pulse sequences are measured and recorded at time intervals ranging from several seconds to as little as (1/oscilloscope bandwidth).

Nominal Pulse Repetition Rate (PRR). The nominal PRR, if any is present, is easily read from an oscilloscope display.

Dither Measurement. Two types of dithering have been observed in UWB devices measured by ITS during this project. One is absolute time-base dither, in which pulses are triggered relative to an absolute time base. The other is relative time-base dither, in which each pulse is triggered at an interval that is measured relative to the preceding pulse, with no reference to a fixed time base. Absolute dither systems may have 50% dither on a pulse-to-pulse basis. Relative time-base systems may have only a 1% dither from pulse to pulse, but the variance in pulse occurrence grows with time. Both types of dither act to suppress lines in resulting emission spectra.

Dither may be observed and documented by triggering a storage oscilloscope on a pulse and then observing the intervals at which subsequent pulses occur. If absolute time-base dithering is occurring, only a few pulses need be measured to document this behavior. If relative time-base dithering is occurring, then a storage oscilloscope is used to trigger on a pulse, and then the display is scrolled for an appropriate length of time (possibly many tens of milliseconds) to observe long-term growth in the dither variance. That is, if the relative time-base dither is 1%, hundreds of pulses must be observed after the trigger pulse to observe the total growth in the variance of pulse-occurrence time.

Gating. Pulse gating is a higher-level modulation of the UWB output, in which the transmitter is quiescent for intervals that are long compared to the nominal pulse repetition interval. Gating is easily observed on an oscilloscope output. It can also usually be measured on a spectrum analyzer in a zero hertz span mode, since the gating intervals are usually on the order of a few milliseconds to tens of milliseconds in duration.

6.4.5 Peak Power Measurements

Peak power may be measured in a bandwidth as described in Section 6.4.3 above. A spectrum analyzer is used to determine peak power in either a spectrum trace or at a single frequency in a zero hertz span mode. Peak power may also be read from an APD curve, as described above.

A significant problem is to measure total peak power in the emission bandwidth of the UWB device. This is not generally feasible in a direct measurement with COTS equipment. ITS equipment is currently capable of measuring peak power in 20 MHz bandwidth at the widest. Although an upgrade to 50 MHz and ultimately 100 MHz is planned for ITS systems, the COTS systems that will accomplish this are known to be expensive, and will require additional calibration routines (requiring dual implementation in software and hardware).

In short, for many laboratories engaged in UWB emission measurements, IF bandwidths between 3 MHz to 10 MHz may be the widest available for the immediate future. And in no case will peak power likely be measured at bandwidths equaling UWB emission bandwidths. Extrapolation to wider bandwidths will be a necessity if wider-bandwidth peak power measurements are required. Extrapolation will require the measurement of the emission in a succession of bandwidths (as the stair-step measurement in Figure 6.4), so that the rate of progression can be measured.

6.4.6 Average Power Measurements

Two averages that are widely used for various purposes are root mean square (RMS) average and logarithmic average. RMS average is the equivalent constant-rate of flow of energy from the transmitter over a time interval that is long compared to the nominal pulse repetition interval. Logarithmic average (average decibels) is required by such regulatory standards as Part 15 of CFR 47.209. While the logarithmic average is sometimes used vernacularly in an interchangeable sense with the term “average power,” it must be stressed that the average decibel level emitted by a transmitter is not equivalent to the RMS (arithmetic mean) average output power level.

Measurement of RMS Average. At least five alternative techniques for using COTS equipment to measure RMS emissions from UWB transmitters have been found to be feasible, as detailed below.

RMS Detector Integrated into a Spectrum Analyzer. As of 2000, most commercially available spectrum analyzers do not incorporate RMS detectors. But as of late 2000 and early 2001, some analyzers with integrated RMS detectors are becoming available on the commercial market. One such analyzer became available to ITS engineers for evaluation purposes just prior to this report's release, too late to be used in the UWB measurements contained in this report. But ITS engineers were able to evaluate the detector's performance characteristics on some UWB signals. The outcome of that preliminary evaluation indicated that this integrated detector appeared to offer a technically feasible solution to the problem of measuring RMS values of UWB emissions. It is anticipated that similar RMS detectors in other newly available spectrum analyzers will be similarly feasible for measurement of UWB average emissions.

Power Meter RMS Measurement.[28] RMS power may be measured directly with a power meter, under some conditions. The power meter must utilize a bolometer-type sensing head. The UWB signal must be at least 10 dB above the thermal noise in the measurement head, so that the power being averaged is primarily an indication of the UWB device emission and not of the thermal noise in the power meter. The limited experience that ITS has in this particular measurement on UWB-like signals has indicated that it is difficult to realize a sufficiently high SNR on UWB signals if measurements are performed on radiated (as opposed to hardline-coupled) signals. Diode-type power meters may have insufficient dynamic range for the required UWB measurements.

Spectral Line Power Measurement. If the UWB device produces a line spectrum (i.e., the signal is not a dithered pulse sequence or other noise emission), then average power may be derived from measured power in a maximum-amplitude spectrum line. The functional relationship is given by Equation 6.5, above.

[28]The measurement of RMS power from UWB devices with power meters was not part of this project.

APD Curve Calculation. RMS may be directly computed from the APD curve for the frequency and bandwidth in question. It may also be computed as the APD is generated.

Computation from Spectral Line Measurement or from Duty Cycle and Peak Power Measurement. The peak power is related to the average power and the power in a maximum-amplitude line by the relationship in Equation 6.5. However, many UWB devices do not generate line spectra.[29] For these devices, average RMS power may be calculated by multiplying the peak power in a bandwidth by the duty cycle. Duty cycle may be measured directly (if pulse width can be measured directly or at least estimated (see above)). Less desirably, from the standpoint of measuring quantities directly, duty cycle may be taken from a specification sheet for the device.

Measurement of Logarithmic Average. A logarithmic average may be measured directly from a spectrum analyzer as follows: With the analyzer in a zero-hertz span mode, set IF bandwidth to a desired value (e.g., 1 MHz, if log average power in 1 MHz is required). Video bandwidth is narrowed to a value on the order of a few hertz. (10 Hz to 10 kHz video bandwidth is specified by some regulatory measurement procedures.) The resulting log (decibel) average is read from the spectrum analyzer display, with some caveats.

The caveats are critical, from a technical standpoint. First, ITS has discovered that some UWB emissions generate log averages that are below measurement system noise, as shown in Figure 6.6. In such a case, the attempted log average measurement converges on the measurement system noise floor rather than the log average emission of the UWB device. Given that the measurement system noise in the widely used COTS preselector was eleven decibels above ambient thermal noise in this case, and that the broadband horn measurement antenna was placed 1 m from the UWB device, it is difficult to design a COTS measurement system that will achieve better SNR on the UWB signal than that shown in Figure 6.6. The failure of the log average technique to indicate only the measurement system noise in this case means that the technique is not generally applicable to UWB devices as a class.

Log average may also be computed from an APD curve, just as for RMS average. But if the log average is below the measurement system noise, the log average will not be computable from the APD curve.

[29] This includes devices that generate line spectra; for example, absolute time-based dither signals generate lines at the interval of a PN code sequence, on the order of 1 kHz or 10 kHz.

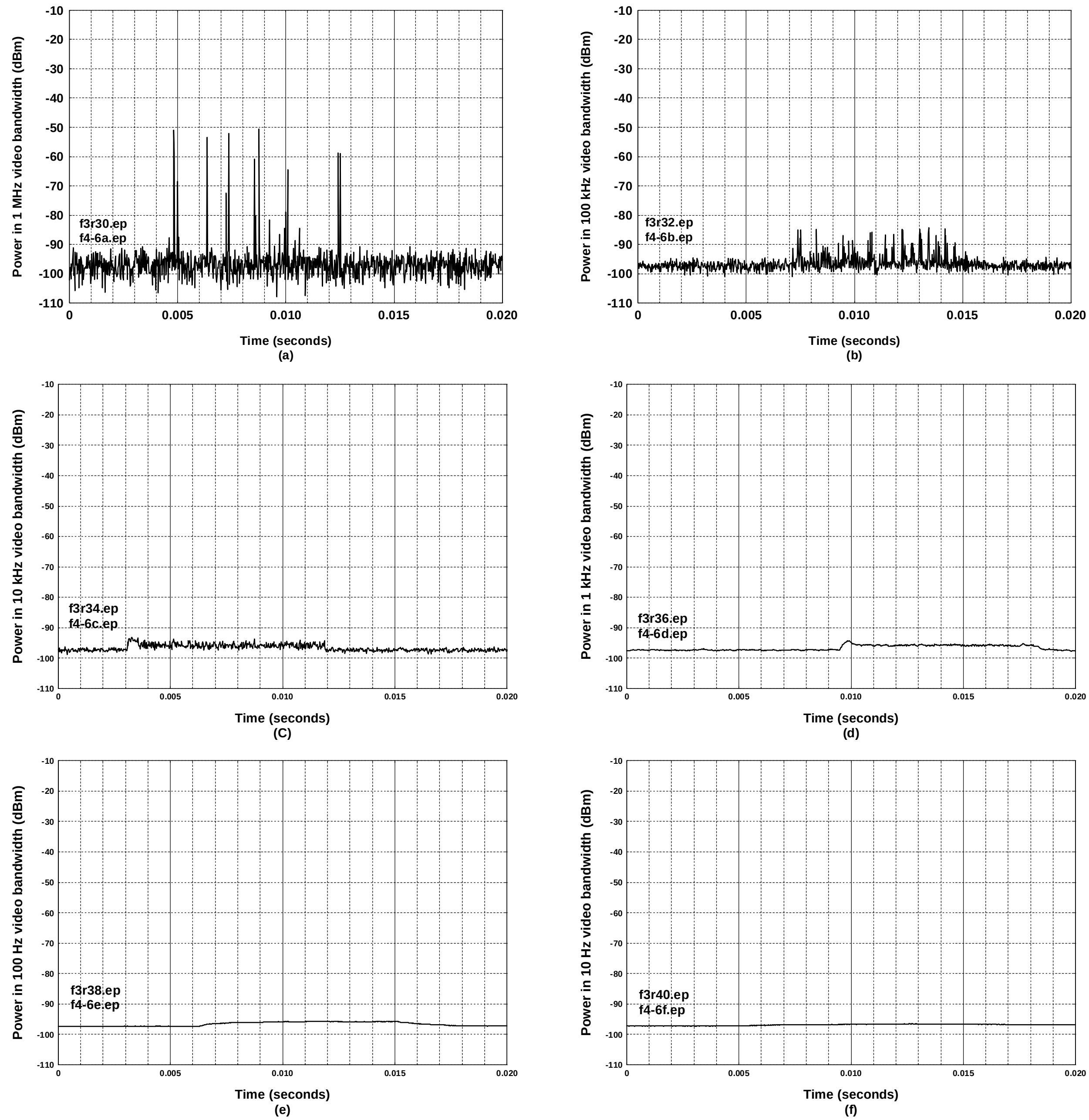

Figure 6.6. Log average measurement for a gated UWB transmitter with a low duty cycle. IF bandwidth = 3 MHz and video bandwidth is narrowed from 1 MHz to 10 Hz ((a) through (f)). This measurement converges on the measurement system noise floor, and thus fails to indicate the device's true log average. Measurement antenna was 1 m from transmitter, and measurement system noise figure was 11 dB. Given that little improvement in signal to noise ratio would be achievable for this measurement with COTS equipment, this serves as an example of the difficulty in assessing average power from all types of UWB transmitters using this technique.

6.5 Summary of Bandwidth Limited Measurement Techniques for UWB Devices

In summary, a UWB measurement system utilizing COTS equipment for bandwidth limited measurements can be achieved with commonly available laboratory hardware. The general measurement configuration may be as shown in Figure 6.3. Low-noise preamplification will often be required. Calibration of measurement equipment is critical, and should include corrections for non-constant aperture measurement antennas.

The primary measurement equipment required includes a spectrum analyzer, an oscilloscope, a discrete-component diode detector, a laptop computer that can perform simple commands and data acquisition on the analyzer and the oscilloscope, and software that can perform limited commands, data retrieval, and data processing as described above.

Emission spectra, bandwidth dependence of emission amplitudes, amplitude probability distributions, pulse repetition rates, pulse dither sequences, and emission gating may be measured. Pulse shapes may be measured as a function of receiver IF bandwidth. Pulse width may be estimated but probably not measured precisely. Peak power in a bandwidth may be measured, and may be estimated for any bandwidth. Average power measurements are more problematic; RMS may be measured directly with an appropriately equipped spectrum analyzer or a power meter (if important conditions are met). Average power may alternatively be estimated with alternative methods. Log average may be directly measured for some UWB devices, but cannot be measured for UWB emitters as a general class.