NTIA Report 03-402

Measurements to Determine Potential Interference to Public Safety Radio Receivers from Ultrawideband Transmission Systems

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June 2003

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EXECUTIVE SUMMARY

This report describes laboratory measurements to determine the extent and nature of interference to Public Safety radio receivers by ultrawideband (UWB) signals. Two Public Safety radio receivers from different manufacturers were tested in the 138-MHz band, both configured for Project 25 digital radio mode and one additionally configured and tested in analog mode. The laboratory measurements were performed by inserting increasing levels of UWB interference and measuring either bit-error rate (BER) for digital radios or signal-plus-noise-plus-distortion to noise-plus-distortion ratio (SINAD) for one of the same radios placed in analog mode.

When put through the passband of the receiver and analyzed in terms of the spectral and amplitude probability statistics, we see that all UWB signals, while initially impulsive, are altered by the passband transfer function to take on characteristics that lie along a continuum from impulsive, to Gaussian noise-like, to sinusoidal. By varying pulse repetition frequency (PRF), pulse spacing schemes, and gating, a variety of UWB signals were generated for these measurements. However, because of the relatively narrow bandwidths of the receiver passband (12.5 kHz), none of the interfering signals were considered impulsive after alteration by the receiver passband transfer function. To be impulsive would have required PRFs significantly less than 12.5 kHz.

Results showed that, when reported in terms of average UWB power in the receiver bandwidth, there is little difference in interference to Public Safety radios when comparing each of the generated UWB signal types. When expressed in terms of signal-to-interference power ratio, where interference power is defined as the power passed through the receiver passband, reference sensitivity (5% BER for digital radios and 12 dB SINAD for analog radios) occurs at approximately 10 dB, with a variation of 2 to 5 dB on either side, depending upon the receiver and signal type. However, there are subtle trends, with gated signals being slightly more invasive and signals with spectral lines being slightly less invasive than signals that are Gauusian noise-like when altered by the receiver passband transfer function. When the interference power is expressed in terms of anything other than the mean power in the receiver bandwidth (e.g., wider bandwidths or peak power), the receiver response can vary greatly depending upon the nature of the interfering signal.

MEASUREMENTS TO DETERMINE POTENTIAL INTERFERENCE TO PUBLIC SAFETY RADIO RECEIVERS FROM ULTRAWIDEBAND TRANSMISSION SYSTEMS

J. Randy Hoffman, Eldon J. Haakinson, Yeh Lo[†]

This report describes laboratory measurements to determine the extent and nature of interference to Public Safety radio receivers by ultrawideband (UWB) signals. Two Public Safety radio receivers from different manufacturers were tested in the 138-MHz band, both configured for Project 25 digital radio mode and one additionally configured and tested in analog mode. The laboratory measurements were performed by inserting increasing levels of UWB interference and measuring either bit-error rate (BER) for digital radios or signal-plus-noise-plus-distortion to noise-plus-distortion ratio (SINAD) for one of the same radios placed in analog mode. By varying pulse repetition frequency (PRF), pulse spacing schemes, and gating, a variety of UWB signals were simulated, which were either Gaussian noise-like, sinusoidal, or a hybrid of the two when passed through the receiver passband. Results showed that, when reported in terms of average UWB power in the receiver bandwidth, there is little difference in interference to Public Safety radios when comparing each of the generated UWB signal types. When expressed in terms of signal-to-interference power ratio, where interference power is defined as the power passed through the receiver passband, reference sensitivity (5% BER for digital radios and 12 dB SINAD for analog radios) occurs at approximately 10 dB, with a variation of 2 to 5 dB on either side, depending upon the receiver and signal type. When the interference power is expressed in terms of anything other than the mean power in the receiver bandwidth (e.g., wider bandwidths or peak power), the receiver response can vary greatly depending upon the nature of the interfering signal.

Key words: impulse radio, interference measurement, noise, Project 25, Public Safety radio systems, radio frequency interference (RFI), ultrawideband (UWB)

1. INTRODUCTION

As new wireless applications and technologies continue to develop, conflicts in spectrum use and system incompatibility are inevitable. This report investigates potential interference to Public Safety radio receivers by ultrawideband (UWB) signals. According to Part 15 of the Federal Communications Commission (FCC) rules, non-licensed operation of low-power transmitters is allowed if interference to licensed radio systems is negligible. On May 11, 2000, the FCC issued a Notice of Proposed Rulemaking (NPRM) [1] which proposed that

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UWB devices operate under Part 15 rules. This would exempt UWB systems from licensing and frequency coordination and allow them to operate under a new UWB section of Part 15, based on claims that UWB devices can operate on spectrum already occupied by existing radio services without causing interference. The NPRM called for further testing and analysis to investigate the risks of UWB interference and ensure that critical radio services are adequately protected.

Conventional methods for measuring and quantifying interference under narrowband assumptions are insufficient for testing UWB interference. Recently, the National Telecommunications and Information Administration's (NTIA's) Institute for Telecommunication Sciences (ITS) studied the general characteristics of UWB signals [2] and the effects of UWB signals on global positioning systems [3] [4]. As a natural extension to these studies, this report describes the investigation of interference from a representative set of UWB signals imposed on a select group of Public Safety radio receivers. The remainder of this section discusses the relevant technologies and associated applications, briefly summarizes related studies, and gives an outline for this report.

1.1 The Technologies

The multifaceted strategic and commercial importance, as well as potential for conflict, of Public Safety radio and UWB systems are summarized in the following subsections.

1.1.1 Ultrawideband Transmission Systems

Unlike conventional radio systems, UWB devices bypass intermediate frequency stages, possibly reducing complexity and cost. Additionally, the high cost of frequency allocation for these devices is avoided if they are allowed to operate under Part 15 rules. These potential advantages have been a catalyst for the development of UWB technologies.

UWB signals are characterized by modulation methods that vary pulse timing and position rather than carrier-frequency, amplitude, or phase. Short pulses (on the order of a nanosecond) spread their power across a wide bandwidth rather than containing it in a narrow band. UWB proponents argue that the power spectral density decreases below the threshold of narrowband receivers, minimizing interference. Other possible advantages are mitigation of frequency selective fading induced by multipath or transmission through materials.

Existing and potential applications for UWB technology can be divided into two groups – wireless communications and short-range sensing. In wireless communications, UWB has been claimed to be an effective way to link many users in multipath environments (e.g., distribution of wireless services throughout a home or office). In short-range sensing applications, it can be used for determining structural soundness of bridges, roads, and runways and locating objects and utilities underground. Potential automotive uses include collision avoidance systems, air bag proximity measurement for safe deployment, and fluid level detectors. UWB technology is being developed for new types of imaging systems that would assist rescue personnel in locating persons hidden behind walls, under debris, or under snow.

1.1.2 Public Safety Radio Systems

Public Safety agencies, including law enforcement, fire, and emergency medical services, use land mobile radio (LMR) systems for communication of voice and data messages. It is anticipated that UWB applications such as ground-penetration radars and through-the-wall-imaging systems will operate with the spectral region of greatest power located below 1 GHz. The Public Safety user might rely on these UWB systems to operate in close proximity to LMR systems under the same operational scenarios – to provide both vital communications and search/rescue sensor information. For these reasons, it is important to determine the potential of interference to LMR Public Safety radio systems from UWB emissions.

1.2 Scope

The objective of these measurements is to measure the interference by different classes of UWB signals to several different Public Safety radio receivers and to observe and report broad trends in Public Safety LMR performance to this interference. No attempt is made to evaluate specific receiver designs or interference mitigation strategies or provide precise degradation criteria. Recommendations on UWB regulation, likewise, are not addressed and lie under the jurisdiction of the policy teams at NTIA's Office of Spectrum Management and the FCC.

1.3 Organization of this Report

Investigation of UWB interference to Public Safety LMR systems encompasses a broad range of expertise including LMR theory of operation, RF design and hardware implementation, and temporal and spectral characterization of interfering signals. This report completely describes the experiment and is organized as follows.

The first three sections provide orientation and background for the reader. Section 2 describes Public Safety LMR and UWB signal characteristics in order to identify potential interference scenarios and rationalize measurement procedures. Section 3 gives a detailed summary of the measurement system, test procedures, UWB-signal sample space, signal generation details, and hardware limitations. Section 4 provides and summarizes the measurement results. Conclusions are drawn in Section 5. The appendix provides a detailed description of each UWB type under test.

2. SIGNAL CHARACTERISTICS

The purpose of this section is to describe Public Safety LMR and UWB signal characteristics in order to identify potential interference scenarios and rationalize measurement procedures.

2.1 Public Safety LMR Systems

Public Safety LMR systems operate in various bands from about 30 MHz to 900 MHz, with bandwidths currently 25-30 kHz; new regulations, however, require the bandwidths to be reduced to 12.5 kHz (and potentially to 6.25 kHz). Both digital and analog modulation schemes are currently utilized for Public Safety LMR communications. For these measurements, two types of modulation standards were used – Project 25[†] digital signals and traditional analog signals. The Project 25 radios used in these measurements have a 4-level frequency shift keyed (C4FM) modulation confined to 12.5-kHz bands. Two-bit symbols are represented by 4 different frequency shifts, each separated by 1.2 kHz. The analog radio-configuration used for these measurements has a 12.5-kHz bandwidth and employs a frequency modulation (FM).

2.2 UWB Signals

The UWB signal is, in general, a sequence of narrow pulses with widths on the order of 0.2 to 10 ns. Uniform pulse spacing (UPS), as the name implies, means the UWB signal has no modulation and the pulses are spaced equally apart. Modulation of the pulses can take on many different forms. One form of digital modulation is pulse-position modulation where, for example, a pulse that is slightly advanced from its nominal position represents a "zero." Likewise, a slightly retarded pulse represents a "one." Another form of digital modulation is on-off keying (OOK) where pulses, in what is normally an evenly spaced sequence, are deleted, thus representing "zeros." In addition to the modulation scheme, the pulses can be dithered, where pulses are randomly located relative to their nominal, periodic location – absolute referenced dithering (ARD), or relative to the previous pulse – relative referenced dithering (RRD). The extent of dither is expressed in terms of the percentage of pulse repetition period, which is the reciprocal of pulse repetition frequency (PRF). For example, 50% absolute referenced dithering describes a situation where the pulse is randomly located

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[†]Project 25 (P25) is a standard developed for Public Safety LMR radio systems to provide digital, narrowband radios with the best performance possible and to permit maximum interoperability. These standards are a joint effort of U.S. Federal, state, and local governments, with support from the U.S. Telecommunications Industry Association (TIA). State Government is represented by the National Association of State Telecommunications Directors (NASTD) and local government by the Association of Public-safety Communications Officials, International (APCO).

in the first half of the period following the nominal pulse location. Finally, some UWB systems employ gating. This is a process whereby the pulse train is turned on for some time and off for the remainder of a gating period.

Four different pulse spacing modes (UPS, OOK, ARD, and RRD) are illustrated in Figure 2.1, whereby the vertical dashed lines represent the ticks of a clock. Gating is represented by the removal of the pulses in the shaded areas; in the case of the UPS example, there are 4 pulses generated during the gated-on time followed by 8 clock ticks for which there are no pulses (to give a duty cycle of 33%).

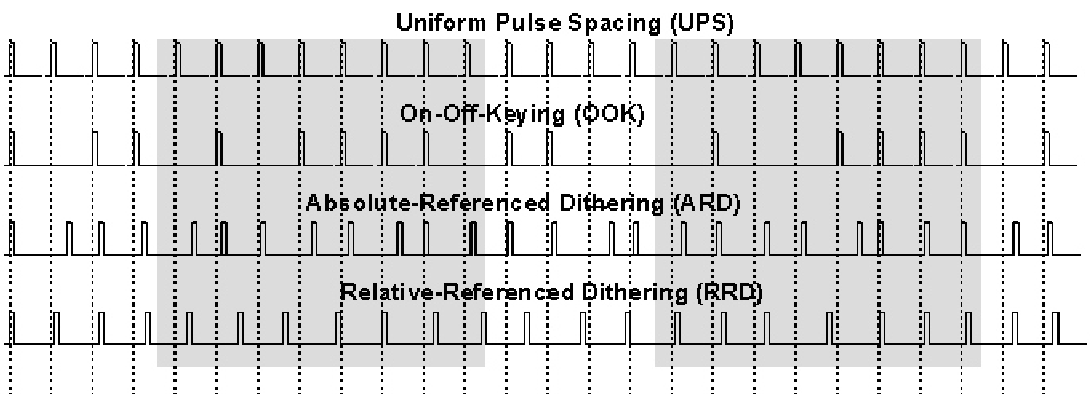

Figure 2.1. Pulse spacing modes.

Spectral Considerations

The frequency domain characteristics (emission spectrum) of a UWB signal are dependent upon the time-domain characteristics described above. The pulse shape/width determines the overall spectral envelope, where the bandwidth is approximately equal to the reciprocal of the pulse width. The manner in which the pulses are sequentially spaced determines the fine spectral features within the confines of the envelope.

Spectral plots are shown in Figure 2.2 for four different UWB signals as they are passed through a bandpass filter.† UPS has the power gathered up into spectral lines at intervals of the PRF. The greater the PRF, the wider the line spacing, and the greater the power contained in each spectral line. OOK also has spectral lines spaced at intervals of the PRF that are superimposed on a continuous noise-like spectrum. Dithered signals have spectral characteristics inherently different from either UPS or OOK. For these measurements, ARD has a pulse spacing that is varied by 50% of the referenced clock period. RRD has a pulse

†While Figure 2.2 shows spectral plots at a center frequency of 1575 MHz, the principles presented herein apply, as well, to the 138-MHz band of interest.

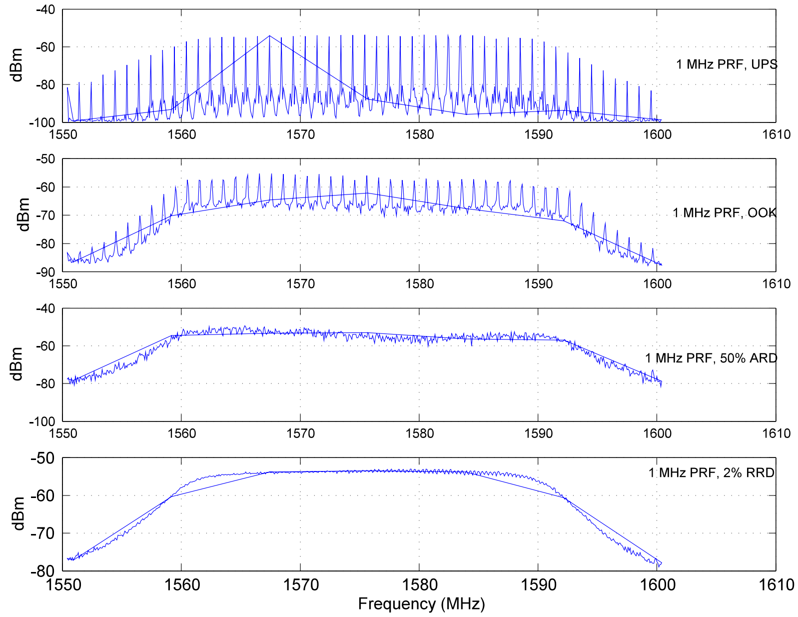

Figure 2.2. Spectral characteristics of the different pulse spacing modes.

spacing that is varied by 2% of the average pulse period. Both of these dithered cases have spectral features that are characteristic of noise (i.e., no spectral lines). The reader is referred to references [2] and [3] for a more in-depth discussion of the spectral characteristics of UWB signals.

Another feature worth noting is the phenomenon of spectral lines spreading due to gating. The spectrum of the gated UWB signal is the result of convolving the non-gated signal with that of a rectangular function, the latter of whose Fourier transform amplitude has a sinc-squared envelope characteristic. It follows that the single line of the non-gated cases is spread out into a multitude of lines confined by the sinc-squared envelope, where the spacing between lines, or line spread spacing (LSS), is equal to the reciprocal of the gating period; null spacing, or line spreading null-to-null bandwidth (LSNB), of the main lobe of the sinc-squared function is equal to two times the reciprocal of gated-on time.

There are two additional spectral features that occur as a result of the signals having been generated by an arbitrary waveform generator (AWG). One is related to how the pattern of pulses is repeated, and the other has to do with the process of placing the pulses into bins, representing discrete dithered pulse spacing. Further discussion of these spectral characteristics of UWB signals is contained in the appendix.

Temporal Characteristics

When a narrow pulse, with a wide bandwidth (BW), is passed through a filter with a narrower bandwidth, the output is essentially equal to the impulse response of the filter; the resultant output has a pulse width approximately equal to the reciprocal of the receiver bandwidth and oscillates at the center frequency of the filter. Figure 2.3 illustrates 50%-ARD signals, at three different PRFs, passed through a 20-MHz bandpass filter (downconverted to an intermediate frequency); the appearance is that of a sinusoid turned on for intervals of 50 ns. The result is that, as the pulse passes through the filter, it becomes wider, the peak-to-average power ratio decreases, and depending upon the PRF and extent of dithering, the pulses may overlap. Because the phase of the oscillation is dependent upon the time origin of the pulse, the phase for adjacent dithered pulses can be asynchronous. This can result in constructive and destructive summation of signal components for overlapping pulses, giving the appearance of random, noise-like signals. OOK signals, while synchronous in phase for adjacent pulses, can have a similar noise-like appearance when adjacent pulses overlap.

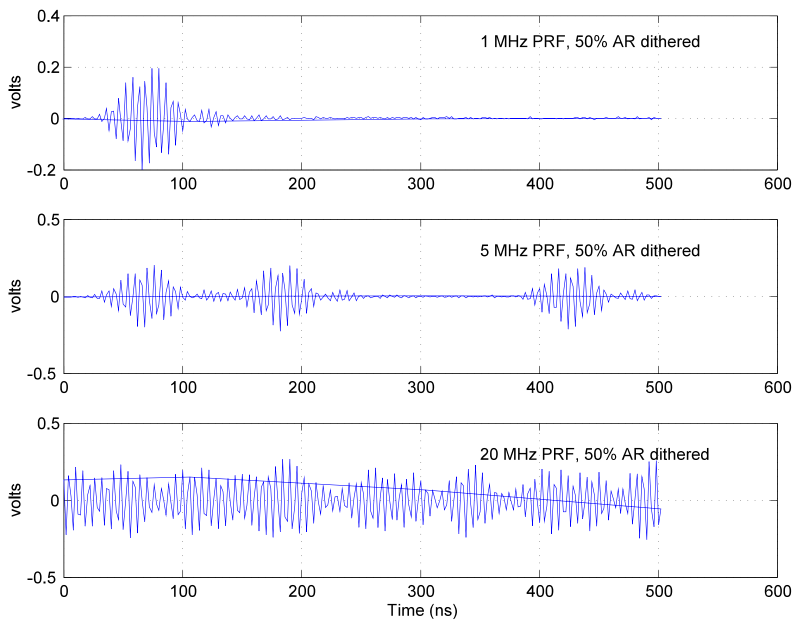

Figure 2.3. Temporal plots of 50%-ARD UWB signals passed through a 20-MHz bandpass filter and downconverted to an intermediate frequency.

3. MEASUREMENT SYSTEM AND PROCEDURES

The purpose of this section is to provide a detailed summary of the measurement system, test procedures, UWB-signal sample space, signal generation details, and hardware limitations for this experiment.

3.1 System

The experimental setup (see Figure 3.1) was comprised of five segments – LMR source, UWB source, continuous-wave (CW) source, noise source, and radio receiver. The system configuration is illustrated in Figure 3.2. Each of the wideband sources (i.e., noise and UWB) were filtered, amplified, and combined prior to input into the receiver. Signal powers were controlled using precision variable attenuators (VA1, VA2, and VA3). The following subsections provide signal-generation details and justification for hardware employed.

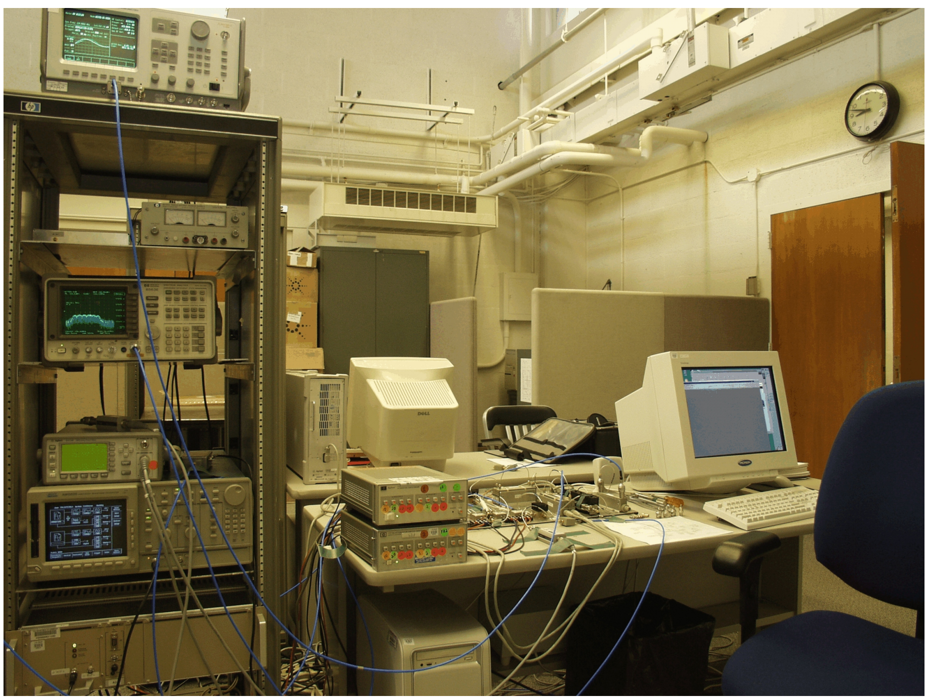

Figure 3.1. Public Safety radio interference test bed.

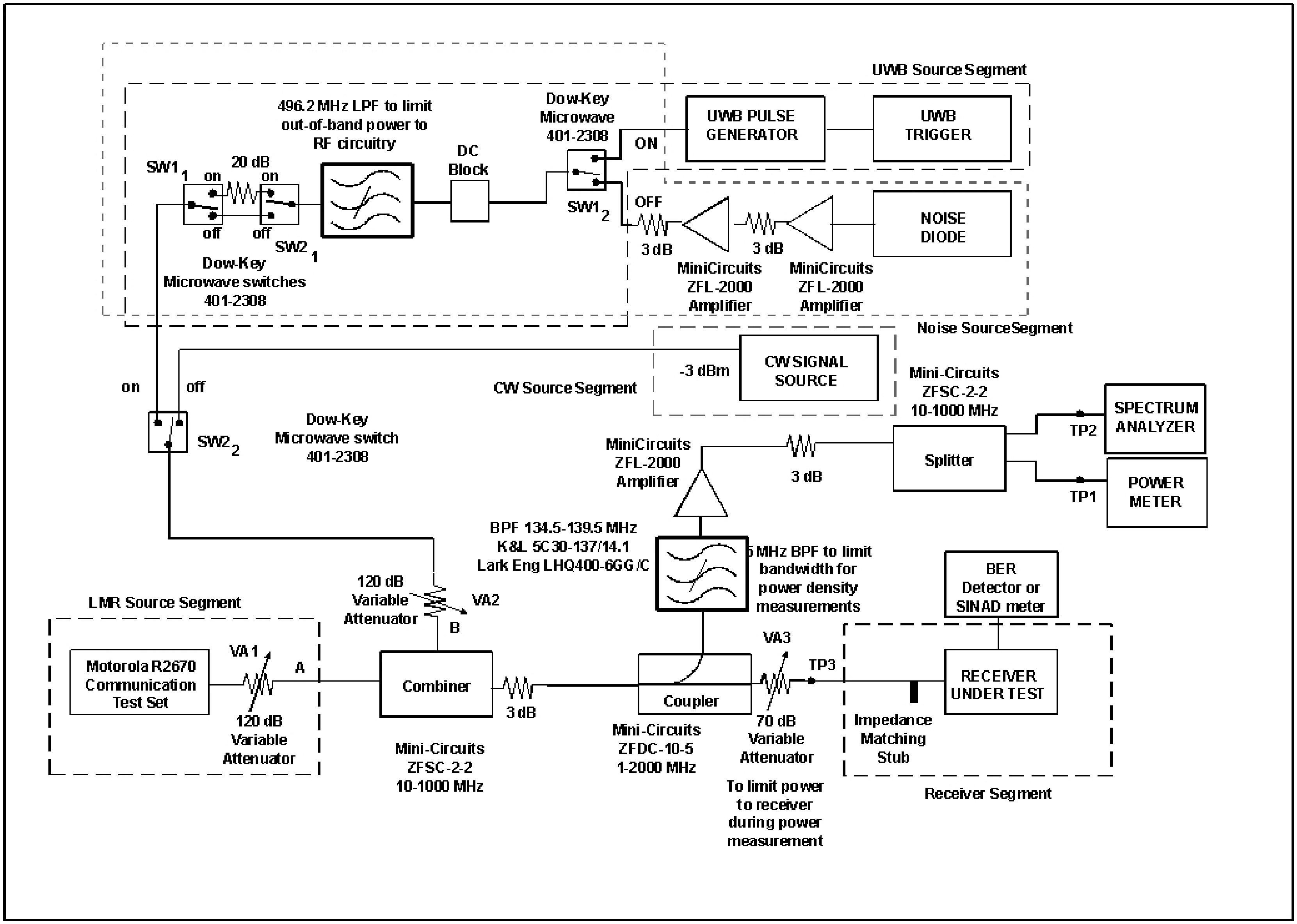

Figure 3.2. Block diagram of measurement system.

3.1.1 LMR Source Segment

The purpose of the LMR signal segment is to provide an emulated Public Safety LMR radio signal. The LMR signal was generated with a Motorola R-2670 Communications Test Set, the output being a digital test tone using a 1.011-kHz CW bit pattern with C4FM modulation. Figure 3.3 shows a frequency histogram of the generated signal as measured on a modulation domain analyzer (all equipment referenced with a rubidium oscillator). The analog test signal was generated by using a 1.0-kHz modulating signal and setting the maximum frequency deviation to 3 kHz. The center frequency for both signal types was 138 MHz. The R-2670 Communication System Analyzer served the additional role of a SINAD meter for analog testing.

3.1.2 UWB Source Segment

The UWB segment consists of a narrow-pulse generator and a triggering device (either an arbitrary waveform generator or a custom built relative-referenced triggering device) to create various signals. Because the pulse shape/width of the UWB signal determines the spectral envelope of the signal, the primary criterion for choosing a UWB pulse generator for these measurements was whether the spectral envelope has no nulls and produces sufficient power across the 138-MHz band of interest.†

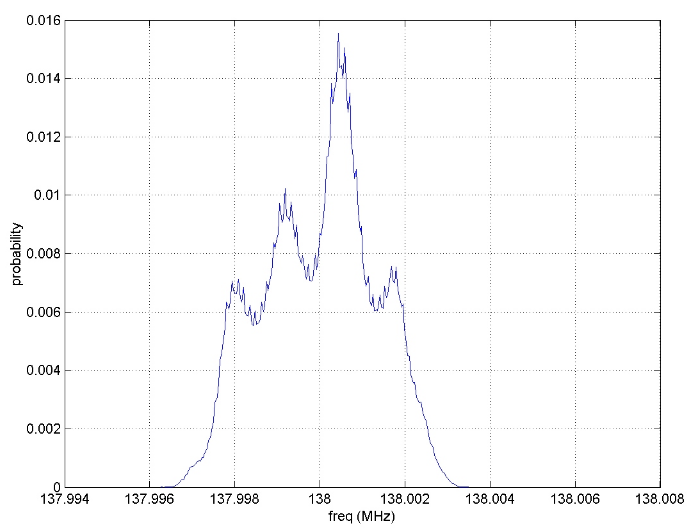

Figure 3.3. Frequency histogram of the C4FM modulated signal.

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†The UWB pulse generator used in these measurements is a Time Domain PG-2000 with impulse voltage rise time (10 - 90%) = 200 ps, impulse fall time (90 - 10%) = 416 ps, impulse width (50%) = 521 ps, and no nulls in the 138-MHz band.

UWB Signal Space

For these measurements, the UWB signal is specified by a combination of mode-of-spacing, PRF, and the application of gating. By varying these three parameters, 11 different permutations were chosen to span a reasonable range of existing and potential UWB signals. For these measurements (as shown in Table 3.1) there are two PRFs (0.1 and 20 MHz), four pulse spacing modes (UPS, OOK, 50%-ARD, and 2%-RRD), and two gating scenarios (no gating and 20% gating with a 4 ms on-time). In addition to these 11 permutations, for measurements with C4FM modulated transmissions, each of the UWB signals with spectral lines have two separate conditions of spectral alignment in relation to the spectral bins noted in Figure 3.3 – one with a spectral line at 138.000506 MHz (aligned with a C4FM frequency shift) and the other with a spectral line at 137.999862 (offset from any C4FM frequency shift). Three of the interference signal types were added as the measurements were in progress, and therefore, were only included with the measurements on one of the receivers; these additional UWB signal types consisted of: 1) 100-kHz PRF, UPS, gated, aligned, 2) 100-kHz PRF, UPS, gated, offset, and 3) 100-kHz PRF, ARD, gated.

Table 3.1. UWB Signal Space

PRF	Pulse Spacing Mode	Gating	Spectral Alignment
100 kHz	UPS	None	Aligned
100 kHz	UPS	None	Offset
100 kHz	UPS	Gated	Aligned
100 kHz	UPS	Gated	Offset
100 kHz	OOK	None	Aligned
100 kHz	OOK	None	Offset
100 kHz	ARD	None	N/A
100 kHz	ARD	Gated	N/A
100 kHz	RRD	None	N/A
20 MHz	UPS	None	Aligned
20 MHz	UPS	None	Offset
20 MHz	UPS	Gated	Aligned
20 MHz	UPS	Gated	Offset
20 MHz	OOK	None	Aligned

Con't Table 3.1. UWB Signal Space

PRF	Pulse Spacing Mode	Gating	Spectral Alignment
20 MHz	OOK	None	Offset
20 MHz	RRD	None	N/A
20 MHz	RRD	Gated	N/A

3.1.3 CW Source Segment

The CW source segment simply consists of a sinusoidal signal produced by a signal generator. The purpose of this segment is to emulate a single spectral line so as to compare the resulting interference to UWB signals also with spectral lines.

3.1.4 Noise Source Segment

The noise source segment consists of Gaussian noise produced by a noise diode. The purpose of this segment is to emulate Gaussian noise interference so as to compare the resulting interference to UWB signals that also have Gaussian noise-like characteristics.

3.1.5 LMR Receiver Segment

Two receivers, A and B, from two different Project 25 (P25) radio manufacturers, were used for measurement. Both receivers were programmed and tested in the P25 digital mode with a 12.5-kHz bandwidth, transmitting in the 138-MHz band. In addition, receiver B was, at a later point, programmed and tested in an analog FM mode, also with a carrier frequency of 138 MHz. Via network analyzer, each device was characterized for input impedance with the radios set to the 138-MHz band. So as to match (zero-reflection) the input impedance to the characteristic impedance of the 50 Ω cables, matching stubs were designed and placed at the antenna input of each radio receiver during measurements. Using a network analyzer to make measurements, Figures 3.4 and 3.5 show the resulting input impedance with the matching stubs in place. From these diagrams, it is clearly seen that the receivers' antenna inputs (after inserting the matching stubs) were closely matched to 50 Ω real impedance with essentially no imaginary component. So as to reduce any coupling of radiated emission into the receivers, each receiver was placed in a shielded box during measurements.

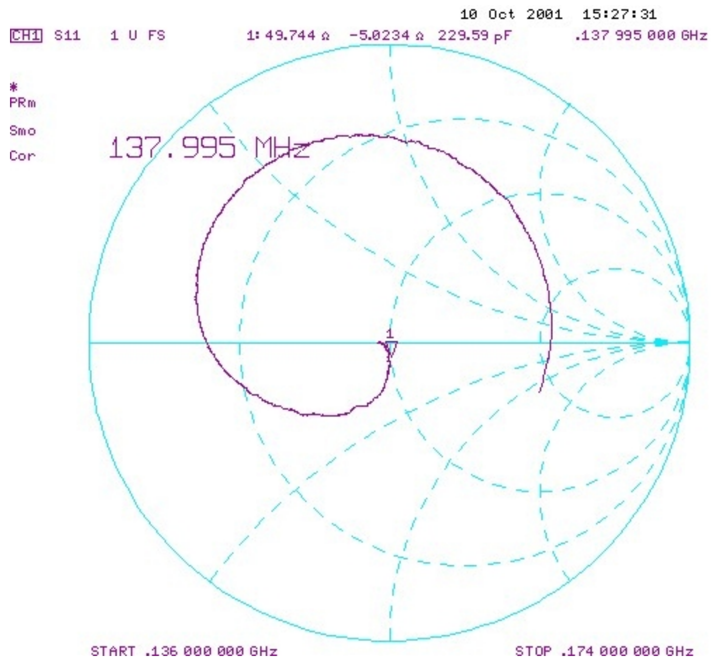

Figure 3.4. Input impedance to receiver A as seen at the input to the matching stub.

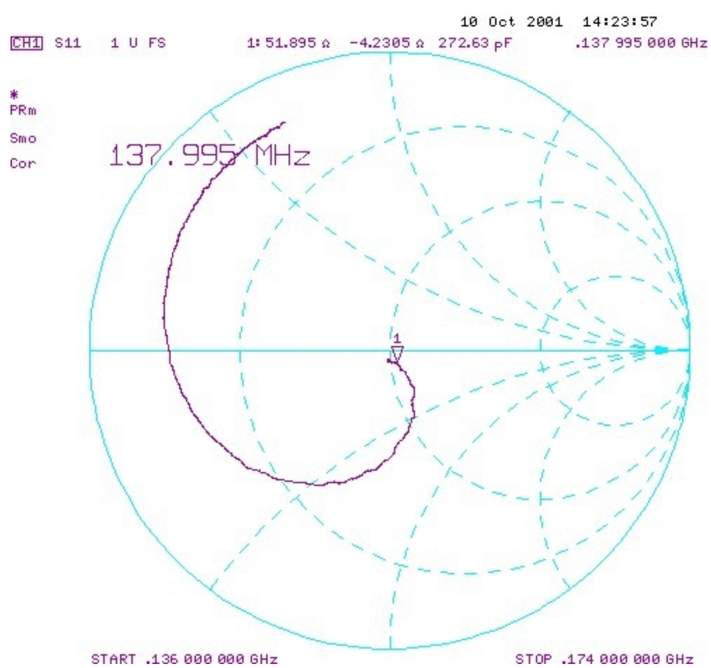

Figure 3.5. Input impedance to receiver B as seen at the input to the matching stub.

3.2 Measurement Procedure

The measurements are performed using the test setup as shown in Figure 3.2. The unwanted signal (UWB, CW, or Gaussian noise) is filtered, amplified, combined with the desired LMR signal, and injected into the Public Safety radio receiver at the antenna port of the receiver under test. Each of the individual signals (unwanted and desired) is independently measured for power using a power meter, with power translated (using calibration factors) to that at the input of the LMR receiver antenna port. For the digital-modulation receivers, measurements are conducted using a 5% BER performance threshold with a UWB signal, CW signal, and Gaussian noise (each separately) as the interfering source. For the analog FM receiver, the same interfering sources are used, but susceptibility measurements are conducted using a 12-dB SINAD performance threshold.

3.2.1 Digital-modulation (P25) Radio Receiver Measurement Procedure

The digital modulation (P25) radio receivers are tested using the process defined in the Project 25 Standards document TIA/EIA-102.CAAA [5]. The procedure described, however, is modified by replacing the description of co-channel interference rejection with in-band interference rejection and making additional desired-signal to interference ratio measurements.

The in-band interference rejection is the ratio of the reference sensitivity to the level of an unwanted input signal. The unwanted signal has an amplitude that causes the BER produced by a wanted signal 3 dB in excess of the reference sensitivity (see definition in step 2 below) to be reduced to the standard BER (in this case, 5%). The method of measurement is described as follows:

1. ***System configuration***: The measurement setup is configured as illustrated in Figure 3.6, with the unwanted signal source connected to terminal B of the combining network.

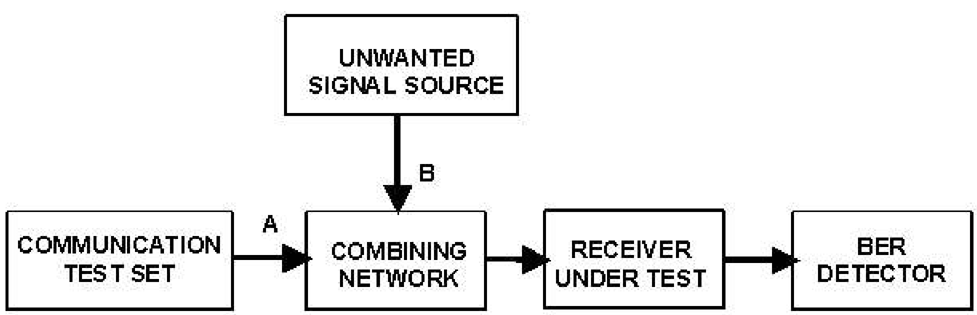

Figure 3.6. Basic block diagram for digital modulation radio receiver measurement.

2. ***Reference power of desired signal in absence of the interfering signal***: In the absence of the unwanted signal (VA2 set to maximum attenuation), the standard 1.011 kHz C4FM modulated tone is applied to terminal A of the combining network. The signal level is reduced to obtain reference sensitivity, defined as the minimum acceptable performance level (MAPL) without an interfering signal. [Note: For P25 receivers, the MAPL occurs with a BER of 5%.] This level is recorded in dBm as P_{REF}.

3. ***Performance versus variable interference power density in the presence of a static desired signal power***:
   a. The level of the wanted input signal is increased by 3 dB and the BER value recorded.
   b. The unwanted input signal (UWB, noise, or CW signal) is applied to terminal B of the combining network.
   c. The unwanted input signal power is increased to reestablish the MAPL. This level is recorded in dBm as P_I.
   d. The in-band interference rejection is calculated as follows:

      $$\textit{in-band interference rejection} = P_{REF} - P_I.$$

   e. The unwanted input signal power is reduced 10 dB in 1-2 dB steps. The level of the unwanted input signal is recorded along with the corresponding value of BER at each step.

4. ***Performance versus variable desired signal power in the presence of a static interference power density***:
   a. The unwanted input signal power is reduced to reestablish the MAPL (P_I).
   b. The level of the wanted input signal is increased approximately 10 dB in 1-2 dB steps. The level of the wanted input signal is recorded along with the corresponding value of BER at each step.

3.2.2 Analog FM Radio Receiver Measurement Procedure

The analog FM radio receivers are tested using a modified version of the process as defined in the FM/PM Standards document TIA/EIA-603. [6] The procedure described, however, is modified by replacing the description of adjacent-channel interference rejection with in-band interference rejection and making additional desired-signal to interference ratio measurements.

Once again, the in-band interference rejection is the ratio of the reference sensitivity to the level of an unwanted input signal. The unwanted signal has an amplitude that causes the SINAD produced by a wanted signal 3 dB in excess of the reference sensitivity (see definition in step 2 below) to be reduced to the standard SINAD (in this case, 12 dB). The method of measurement is described as follows:

1. ***System configuration***: The measurement setup is configured as illustrated in Figure 3.7, with the unwanted signal source connected to terminal B of the combining network.

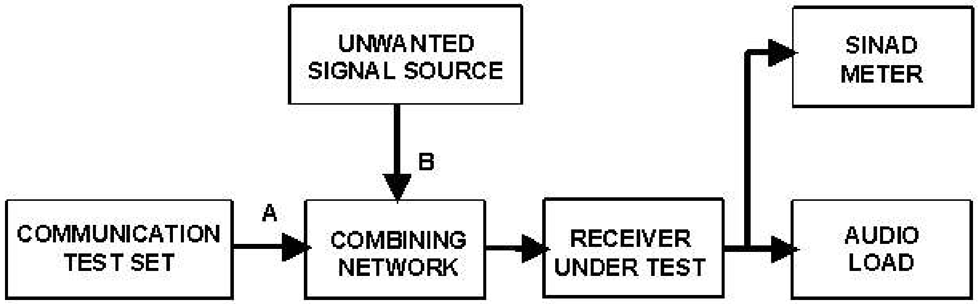

Figure 3.7. Basic block diagram for analog radio receiver measurement.

2. ***Reference power of desired signal in absence of the interfering signal***: In the absence of the unwanted signal (VA2 set to maximum attenuation), the standard 1.0-kHz FM modulated tone (3-kHz maximum frequency deviation) is applied to terminal A of the combining network. The signal level is reduced to obtain MAPL without an interfering signal. [Note: For Public Safety analog FM receivers, the MAPL occurs with a SINAD of 12 dB.] This level is recorded in dBm as P_{REF}.

3. ***Performance versus variable interference power density in the presence of a static desired signal power***:
   a. The wanted input signal power is increased by 3 dB and the SINAD value recorded.
   b. The unwanted input signal (UWB, noise, or CW signal) is applied to terminal B of the combining network.
   c. The unwanted input signal power is increased to reestablish the MAPL. This level is recorded in dBm as P_I.
   d. The in-band interference rejection is calculated as follows:
   $$\textit{in-band interference rejection} = P_{REF} - P_I.$$
   e. The unwanted input signal power is reduced 10 dB in 1-2 dB steps. The level of the unwanted input signal is recorded along with the corresponding value of SINAD at each step.

4. ***Performance versus variable desired signal power in the presence of a static interference power density***:
   a. The unwanted input signal power is reduced to reestablish the MAPL (P_I).
   b. The wanted input signal power is increased approximately 10 dB in 1-2 dB steps. The level of the wanted input signal is recorded along with the corresponding value of SINAD at each step.

Because of receiver differences with regard to the way BER and SINAD are determined, there are some variations in sample size between the different receivers and their modulation modes. The bit errors for Receiver A are reported for each consecutive set of 1728 bits. A minimum of 20 of these values were recorded, averaged, and then divided by 17.28 to give a percent bit error. The bit errors for Receiver B in P25 mode are reported for each consecutive set of 96,960 bits. The percent bit error, therefore, was determined by reading a value from the device and then dividing by 969.6. The SINAD value for Receiver B in analog mode is determined by an analog SINAD meter located in the communication test set. A large enough population was sampled to give a standard deviation of 1 dB in interference signal power.

3.3 Power Measures, Settings, Calibration and Frequency Precision

The purpose of this section is to clarify power measurement terminology, discuss power level settings of the various signal sources, and describe the calibration procedures used to assure the proper power levels.

3.3.1 Calibration and Power Level Correction

For these measurements, all signal powers were measured with a thermoelectric power meter and expressed as a mean value. Wideband sources, such as UWB signals and noise, are expressed in terms of power density in a 1-MHz bandwidth (centered at 138 MHz). This section describes the various steps taken to assure power-level accuracy.

To assure that no test-fixture amplifier became saturated throughout the measurements and to verify functionality, powers were measured (via power meter) throughout the test fixture using the full range of signals and levels that exceeded those used during the measurements. Amplifiers, in addition, were tested for input-to-output linearity – also using the same range of signals and powers.

At the beginning of each day of measurement, calibrations were performed to verify proper operation and to determine a correction factor for proper referencing. As noted in Figure 3.2, the power is measured at the input to the power meter at point TP1. However, the results are reported in terms of the power at the input to the device under test at point TP3. The correction factor used to compensate for the difference in gains between these two paths is obtained by measuring, at these two points, the power of a 138-kHz CW signal supplied by the signal generator at switch SW2 and then adding the difference to each of the powers measured at TP1. During these calibration measurements, attenuation is set to 0 dB at VA3 and maximum at VA1.

Because of the manner in which the interfering power is typically stated in regulatory documents, UWB power is reported in these measurements as the power transmitted across a 1-MHz “brick-wall” bandpass filter centered at 138 MHz, giving a value stated here as the 1-MHz Bandwidth Power Density (1-MBPD). The actual filter (5-MHz bandpass filter) used has a more gradual rolloff and a bandwidth wider than 1 MHz. The correction factor used to compensate for the difference in transmitted power between these two filters is obtained by first measuring, via spectrum analyzer, the squared frequency amplitude response of the "actually-used" filter for each wideband interfering signal (UWB signal and Gaussian noise). To obtain the transmitted power received through the filters, the resulting functions for each of the wideband signals are integrated over the entire band between the stopbands of the "actually-used" filter and then once again across a 1-MHz bandwidth centered at 138 MHz. The correction factor for each wideband signal is the difference in dB of the transmitted power through the "actually-used" filter and the "brick-wall" filter.

Another issue regarding power settings has to do with measuring and setting the power of gated signals. Because the reaction time of a power meter is too fast to allow accurate measurement of gated signals, the power meter was configured to average 20 separate readings; this procedure (empirically determined) stabilized the output of the meter and showed values consistent with the non-gated case – a difference of 7 dB. (Twenty percent gating reduces mean non-gated signal power by 7 dB.) The power of all gated signals used during these interference measurements is expressed, depending upon the circumstance, as either the average power or the average power of the equivalent non-gated signal (i.e., the power of the gated-on time portion of the signal).

3.3.2 Frequency Precision

Because it is necessary to precisely place spectral lines of the interfering signals in relation to the spectral features of the desired signal (within a few tens of Hz), it is necessary to reference several instruments with a single oscillator. For these measurements, a rubidium oscillator was used to reference the AWG, the desired signal source (Motorola Communications Test Set), the CW signal source, and the spectrum analyzer.

4. MEASUREMENT RESULTS

The purpose of this section is to describe the tabular and graphical compilation of the measurements results and, in turn, to summarize. Conclusions are provided in the subsequent section.

4.1 Description of Compiled Measurement Results

The powers of the desired signals at MAPL (P_{REF}) for Receiver A (P25 mode), Receiver B (P25 mode), and Receiver B (analog mode) are −121 dBm, −117 dBm, and −119 dBm respectively. Table 4.1 shows the in-band interference rejection for receiver A (P25 mode) and receiver B (P25 and analog modes) when subjected to the various UWB signals, Gaussian noise, and CW signals – all powers measured in a 1-MHz bandwidth. Figure 4.1 shows the same data in a graphical form. Lower interference rejection values indicate that the interference source is less harmful. Thus, these data show that, when using the 1-MBPD method of measurement, Gaussian noise at a -12 dB rejection value is more benign than a CW signal which has a 6 or 7 dB rejection value. While the labels show signals with spectral lines to be “aligned” or “offset” (as described in Section 3.1.2), this only applies to the receivers in P25 mode and does not apply to the analog case. As mentioned in Section 3.1.2, three additional measurements were added to Receiver B as the measurements were in progress, and therefore are not included in the results for Receiver A; this is denoted by dashed lines in Table 4.1.

Table 4.1. In-band Interference Rejection (P_{REF} - P_I) in dB

Signal Type	Receiver		
	Receiver A - P25 Mode	Receiver B - P25 Mode	Receiver B - Analog Mode
Gaussian Noise	-12	-13	-15
CW, Aligned	7	6	3
CW, Offset	6	7	N/A
UWB, 100-kHz PRF, UPS, Non-gated, Aligned	-3	-5	-6
UWB, 100-kHz PRF, UPS, Non-gated, Offset	-4	-5	N/A
UWB, 100-kHz PRF, UPS, Gated, Aligned	-----	-10	-10
UWB, 100-kHz PRF, UPS, Gated, Offset	-----	-11	N/A
UWB, 100-kHz PRF, OOK, Non-gated, Aligned	-5	-5	-7
UWB, 100-kHz PRF, OOK, Non-gated, Offset	-6	-4	N/A
UWB, 100-kHz PRF, ARD, Non-gated	-11	-12	-14
UWB, 100-kHz PRF, ARD, Gated	-----	-21	-20

Con't Table 4.1. In-band Interference Rejection (P_{REF} - P_I) in dB

Signal Type	Receiver		
	Receiver A - P25 Mode	Receiver B - P25 Mode	Receiver B - Analog Mode
UWB, 100-kHz PRF, RRD, Non-gated	-10	-11	-14
UWB, 20-MHz PRF, UPS, Non-gated, Aligned	8	6	4
UWB, 20-MHz PRF, UPS, Non-gated, Offset	4	5	N/A
UWB, 20-MHz PRF, UPS, Gated, Aligned	0	-1	0
UWB, 20-MHz PRF, UPS, Gated, Offset	-1	-1	N/A
UWB, 20-MHz PRF, OOK, Non-gated, Aligned	8	6	3
UWB, 20-MHz PRF, OOK, Non-gated, Offset	6	5	N/A
UWB, 20-MHz PRF, RRD, Non-gated	-11	-13	-17
UWB, 20-MHz PRF, RRD, Gated	-20	-20	-24

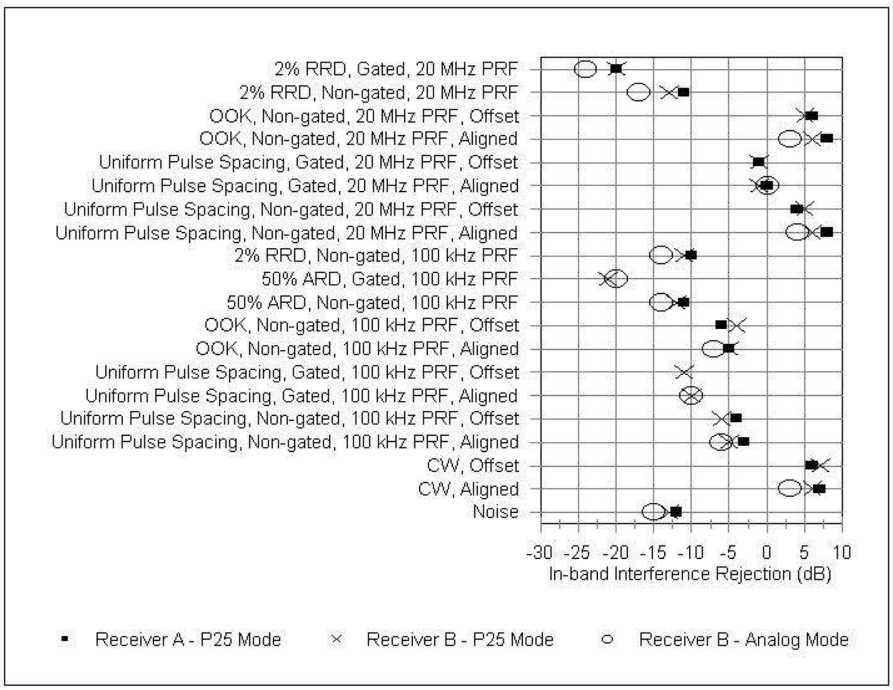

Figure 4.1. In-band interference rejection ($P_{REF} - P_I$).

Figures 4.2, 4.3, 4.6, and 4.7 show P25 radio receiver performance versus variable interference 1-MBPD in the presence of a static desired signal power (described in Section 3.2.1). Figures 4.10 and 4.11 show the same type of plots for Receiver B in analog mode. The thick horizontal line in all of these graphs represents the receiver performance when the LMR signal is held 3 dB above reference sensitivity and no interfering signal is being injected; therefore each of the plots should asymptotically approach this line as the interfering signal power becomes small enough that the primary source of noise is due to the receiver system noise. Signal-to-interference power ratio measured in a 1-MHz bandwidth can be determined by adding 3 dB to P_{REF} for the corresponding receiver and dividing by the values on the abscissa.

Figures 4.4, 4.5, 4.8, and 4.9 show P25 radio receiver performance versus variable desired signal power in the presence of a static interference 1-MBPD (described in Section 3.2.2). Figures UWB 4.12 and 4.13 show the same type of plots for Receiver B in analog mode.

Some of the measurements shown in Figures 4.4 through 4.13 would seem to indicate that CW signals and higher-PRF, non-dithered UWB signals are particularly interfering to LMR receivers. This conclusion is largely an artifact of the way the tests were initially conducted. In particular, the power of the UWB interfering signal was measured in a 1-MHz bandwidth and the average UWB power per MHz was plotted on the graphs. However, some UWB signals (especially high PRF UPS signals) have an average power that varies greatly as a function of frequency. The tests were performed so that the frequencies of highest power were made to coincide with the receiver test frequencies. Therefore, although all UWB test signals may have had equal amplitudes when averaged across a wide bandwidth, they may have represented greatly different amplitudes actually appearing within the 12.5-kHz receiver passband.

Figures 4.14 through 4.19 replot the measurements shown in Figures 4.4 through 4.13. In this case, however, the plots show performance versus signal-to-interference ratio (S/I) in the presence of a static desired signal power, but the interference power is expressed in terms of the mean power passed through a 12.5-kHz filter centered at 138 MHz, the same as the receiver bandwidth. For purposes of brevity this power will be referred to as the Receiver Bandwidth Mean Power Density (RxBMPD). Obtaining the RxBMPD is accomplished by adding, in dB, a bandwidth correction factor for each of the interfering signal powers expressed as a 1-MBPD. The power of any Gaussian noise-like signals (including 50%-ARD and 2%-RRD) is simply corrected by using the following equation:

$$P_{12.5\ \mathrm{kHz}} = \mathit{1\text{-}MBPD} + 10\ \mathrm{Log}_{10}\,(12.5\mathrm{e}3\ /\ 1\mathrm{e}6),$$

where $P_{12.5\ \mathrm{kHz}}$ represents the power in dBm passed through the 12.5-kHz filter.

The power of interfering signals with spectral lines, such as CW and UPS signals, is corrected by determining the ratio of the number of spectral lines in a 1-MHz bandwidth compared to the number of spectral lines passing through the receiver filters; therefore,

$$P_{12.5\ \mathrm{kHz}} = \mathit{1\text{-}MBPD} + 10\ \mathrm{Log}_{10}\,(N_{12.5\ \mathrm{kHz}}\ /\ N_{1\ \mathrm{MHz}}),$$

where $N_{12.5\ \mathrm{kHz}}$ and $N_{1\ \mathrm{MHz}}$ represent the number of spectral lines in 12.5 kHz and 1 MHz respectively for the corresponding interfering signal types.

As reported in Appendix D of [3], the total OOK signal power passed through a filter of bandwidth *B* is

$$\frac{|P(f_c)|^2}{4T^2}[N+TB],$$

where $|P(fc)|^2$ is the power density at f_c for a single pulse, T is the pulse repetition period (i.e. 1/PRF), and N is the nominal number of lines in the filter bandwidth. It follows that, for the same center frequency (f_c), the power ratio for OOK signals passed through two different bandwidths can be expressed as

$$\frac{W_1}{W_2} = \frac{[N_1 + TB_1]}{[N_2 + TB_2]},$$

where W_1 is the power passed through the filter with bandwidth B_1, and N_1 is the number of spectral lines passed through the same filter. The same subscript notation applies to the denominator, where W_2 is the power passed through the filter of bandwidth B_2. The power of OOK signals is therefore corrected using the following equation:

$$P_{12.5\ \mathrm{kHz}} = \mathit{1\text{-}MBPD} + 10\ \mathrm{Log}_{10}\ ([N_{12.5\ \mathrm{kHz}} + T \cdot 12.5\mathrm{e}3] / [N_{1\ \mathrm{MHz}} + T \cdot 1\mathrm{e}6]).$$

As shown in the following equation, power expressed as a mean power for the gated signals will be 7 dB less than the power measured only during the gated-on time:

$$P_M = P_G + 10\ \log_{10}\ (\mathit{gating\ duty\ cycle}),$$

where P_M is the mean power in dBm, P_G is the power in dBm during the gated-on time, and the *gating duty cycle* is the fractional time the signal is gated-on (20% gated-on for these measurements).

Table 4.2 shows these bandwidth correction factors in dB applied to the 1-MBPD[†] of each of the signal types in order to obtain the mean power passed through a 12.5-kHz filter centered at 138 MHz.

[†]1-MBPD of all gated signals is expressed in terms of the power during the gated-on time.

Table 4.2. Power Correction Factors (dB)

Signal Type	Correction Factor (dB)
noise	-19.0
CW, offset	0.0
CW, aligned	0.0
100 kHz, 50%-ARD	-19.0
100 kHz, 2%-RRD	-19.0
100 kHz, UPS, offset	-10.0
100 kHz, UPS, aligned	-10.0
100 kHz, OOK, offset	-12.5
100 kHz, OOK, aligned	-12.5
20 MHz, 2%-RRD	-19.0
20 MHz, UPS, offset	0.0
20 MHz, UPS, aligned	0.0
20 MHz, OOK, offset	-0.2
20 MHz, OOK, aligned	-0.2
20 MHz, UPS, gated, offset, mean power	-7.0
20 MHz, UPS, gated, aligned, mean power	-7.0
20 MHz, 2%-RRD, gated, mean power	-26.0

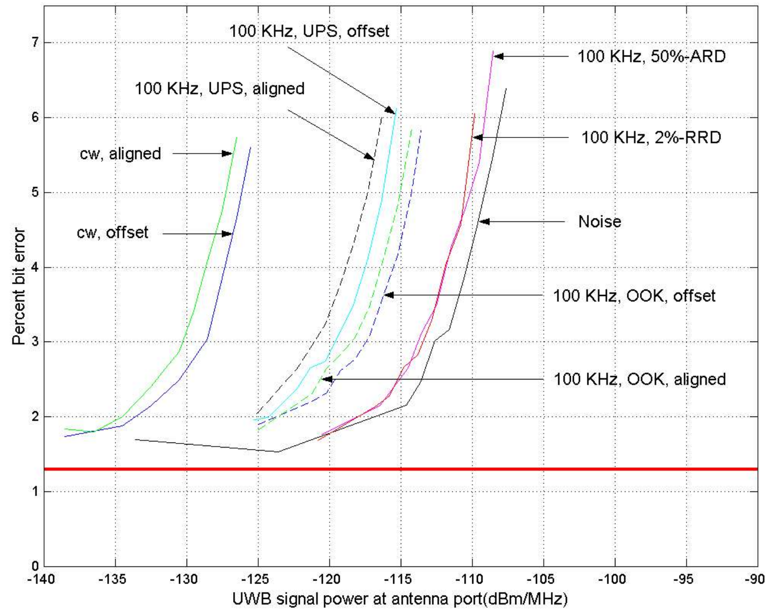

Figure 4.2. Percent bit-error versus variable interference power density for Receiver A in P25 mode – 100-kHz PRF UWB interference.

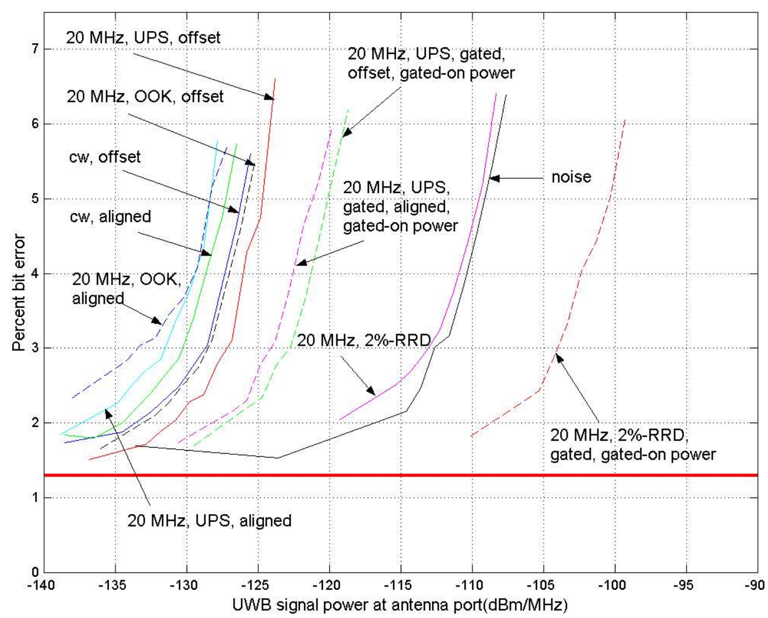

Figure 4.3. Percent bit-error versus variable interference power density for Receiver A in P25 mode – 20-MHz PRF UWB interference.

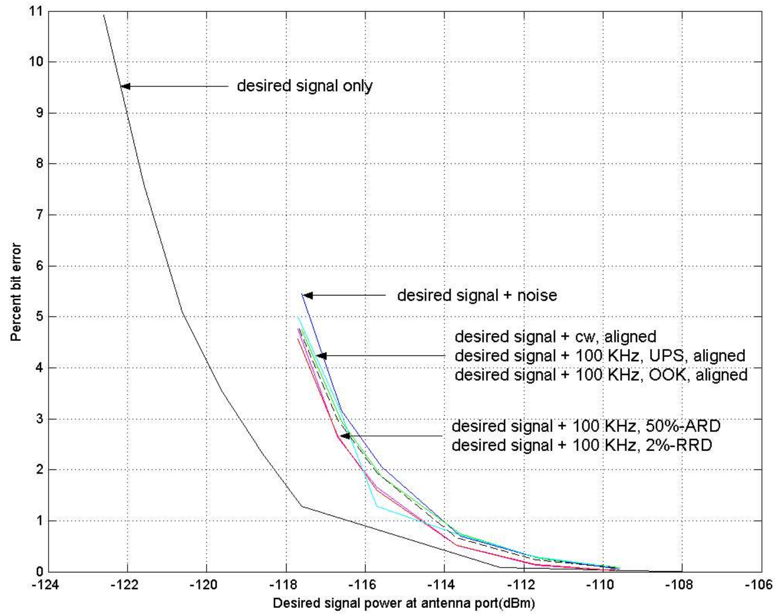

Figure 4.4. Percent bit-error versus variable LMR power for Receiver A in P25 mode – 100-kHz PRF UWB interference.

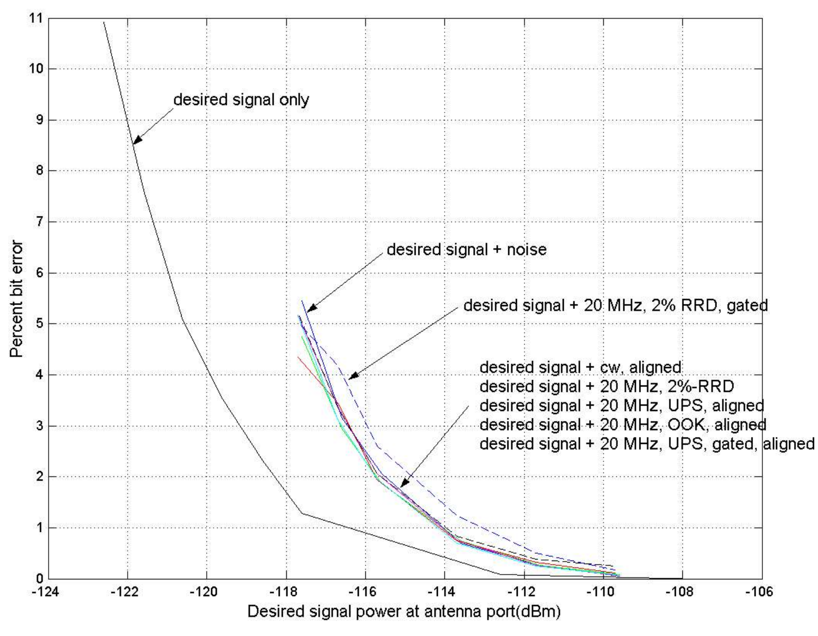

Figure 4.5. Percent bit-error versus variable LMR power for Receiver A in P25 mode – 20-MHz PRF UWB interference.

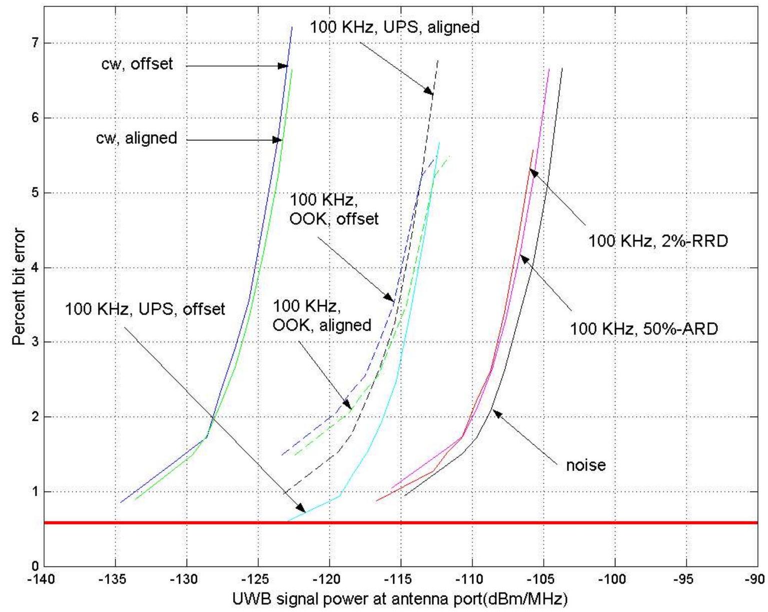

Figure 4.6. Percent bit-error versus variable interference power density for Receiver B in P25 mode – 100-kHz PRF UWB interference.

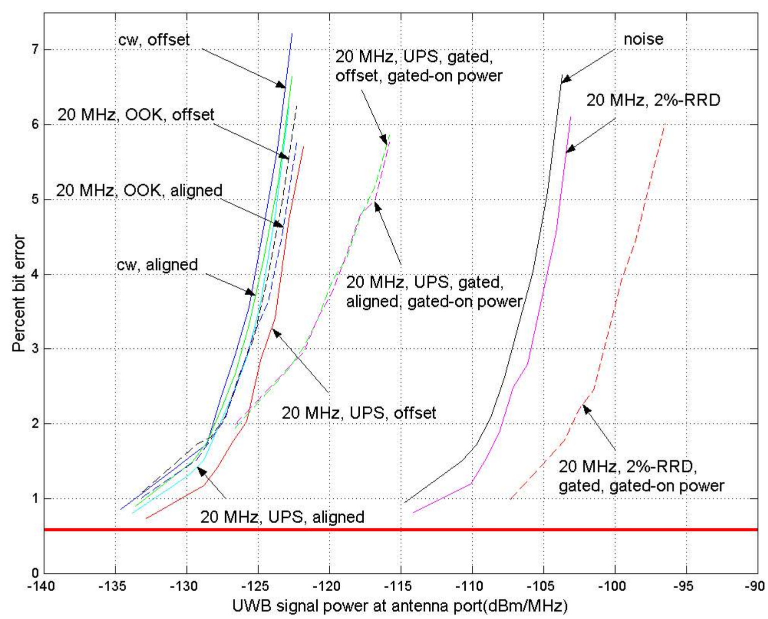

Figure 4.7. Percent bit-error versus variable interference power density for Receiver A in P25 mode – 20-MHz PRF UWB interference.

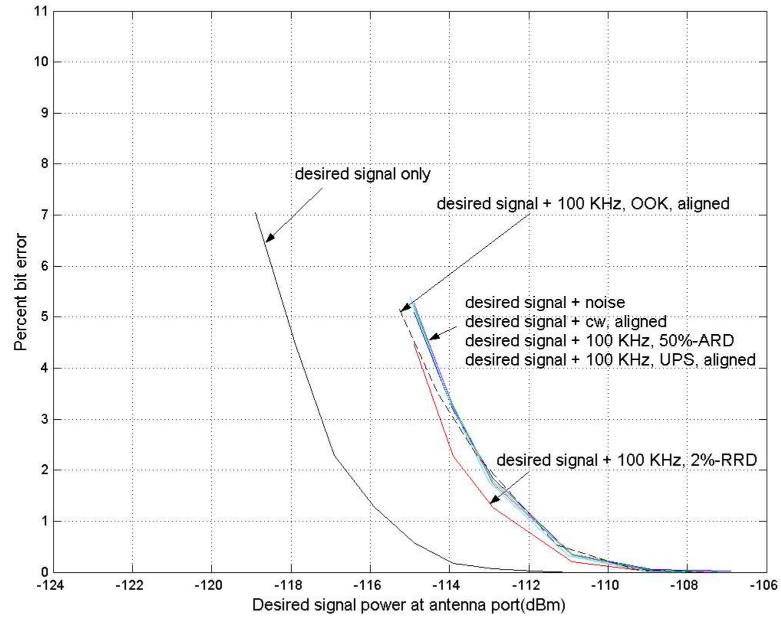

Figure 4.8. Percent bit-error versus variable LMR power for Receiver B in P25 mode – 100-kHz PRF UWB interference.

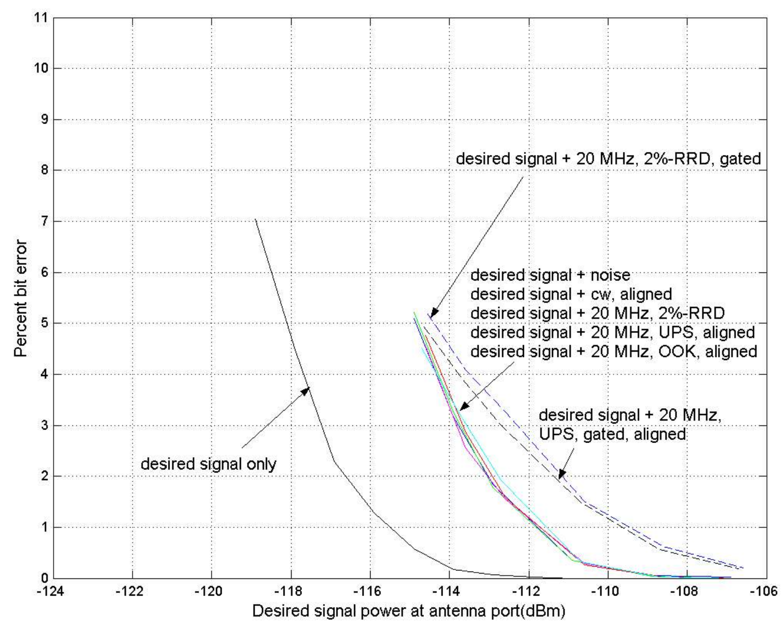

Figure 4.9. Percent bit-error versus variable LMR power for Receiver B in P25 mode – 20-MHz PRF UWB interference.

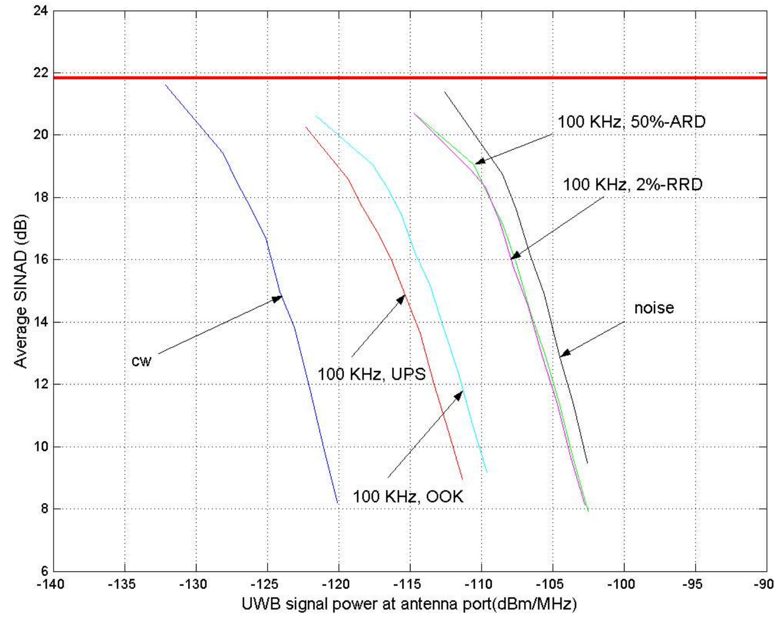

Figure 4.10. Average SINAD versus variable interference power density for Receiver B in analog mode – 100-kHz PRF UWB interference.

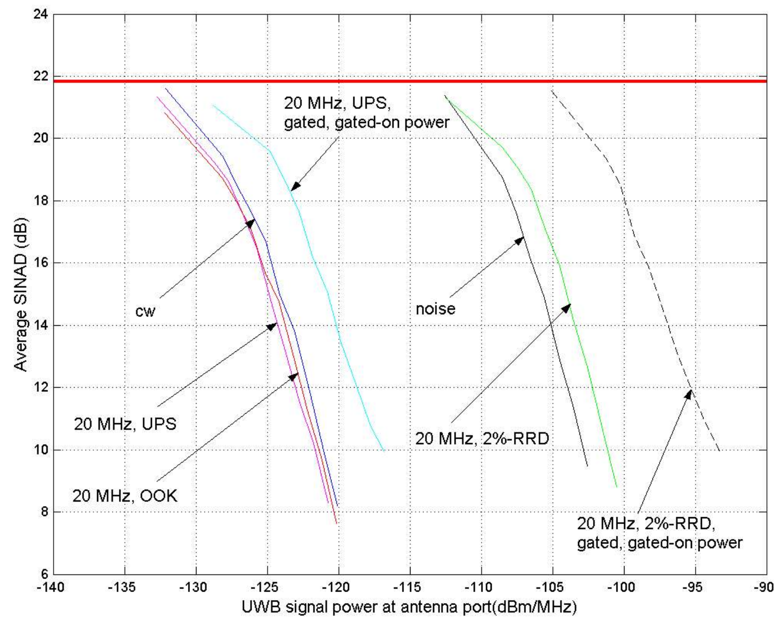

Figure 4.11. Average SINAD versus variable interference power density for Receiver B in analog mode – 20-MHz PRF UWB interference.

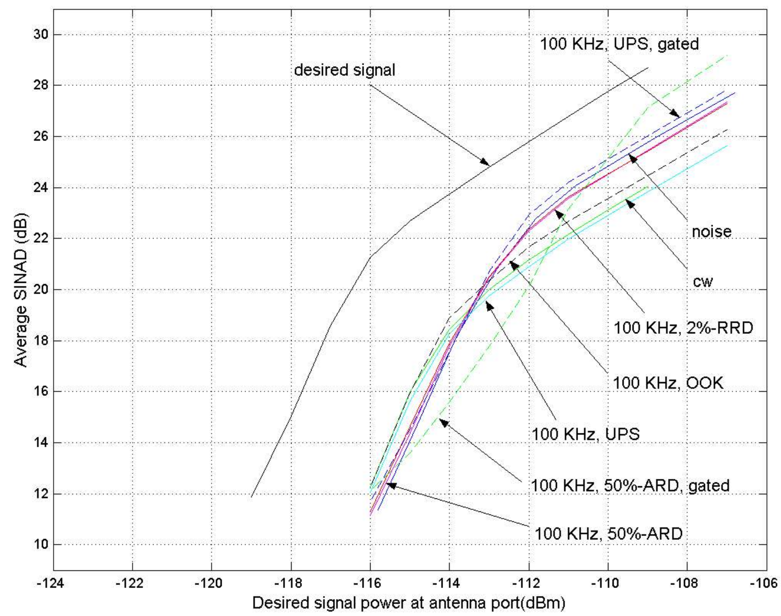

Figure 4.12. Average SINAD versus variable LMR power for Receiver B in analog mode – 100-kHz PRF UWB interference.

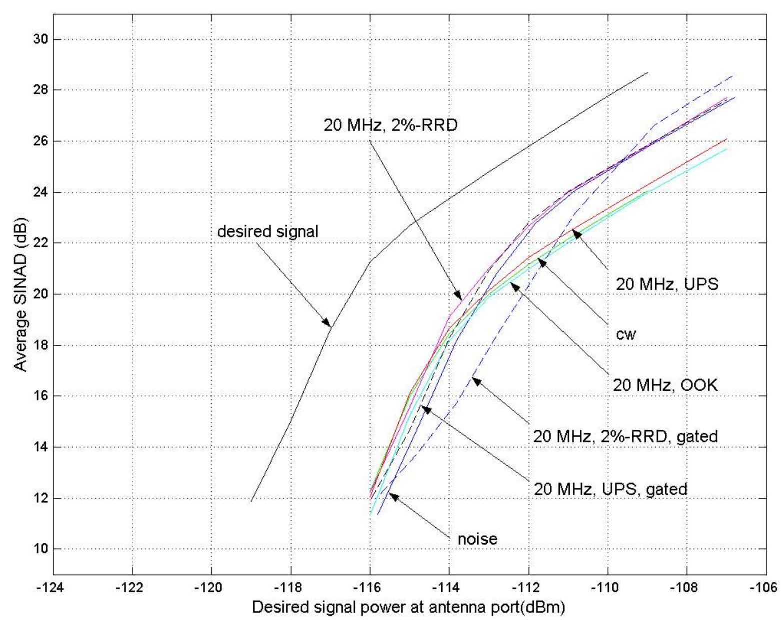

Figure 4.13. Average SINAD versus variable LMR power for Receiver B in analog mode – 20-MHz PRF UWB interference.

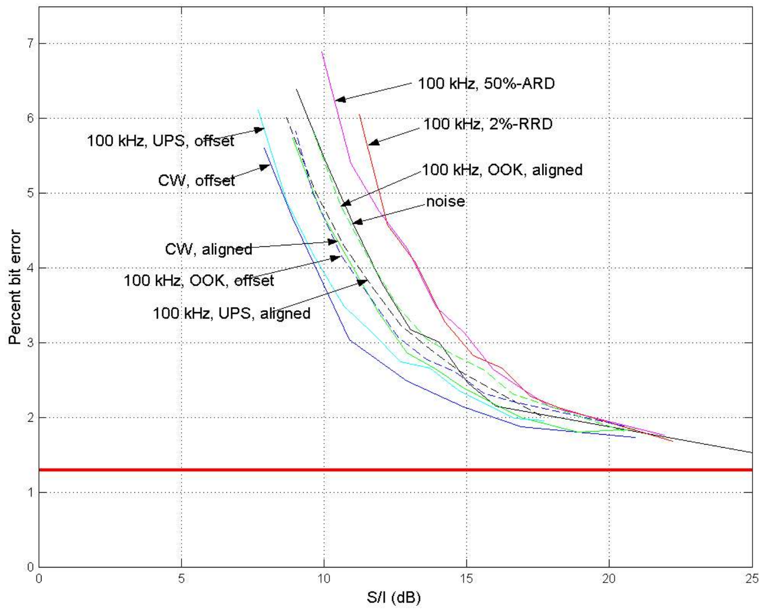

Figure 4.14. Percent bit-error versus S/I for Receiver A in P25 mode – 100-kHz PRF UWB interference.

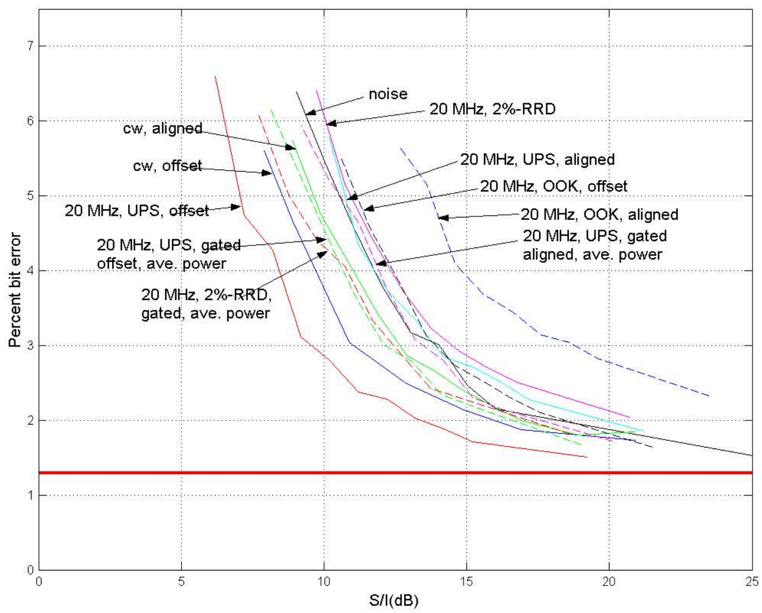

Figure 4.15. Percent bit-error versus S/I for Receiver A in P25 mode – 20-MHz PRF UWB interference.

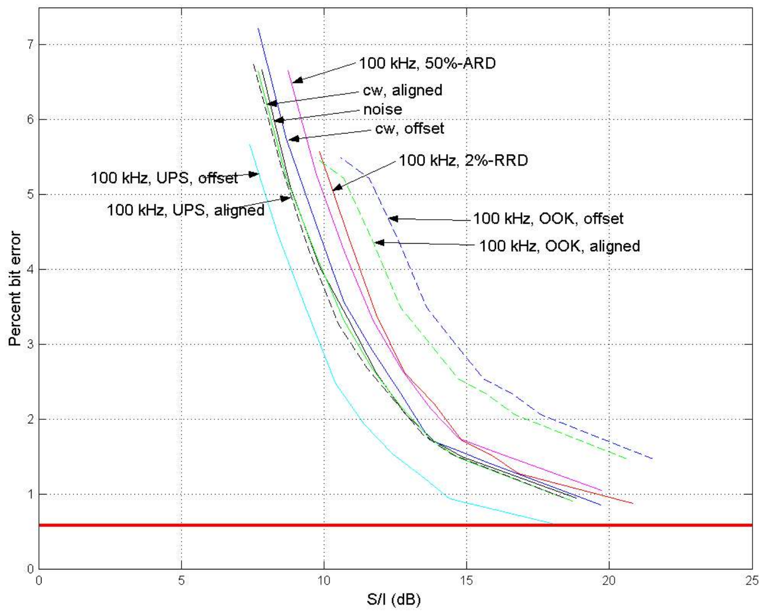

Figure 4.16. Percent bit-error versus S/I for Receiver B in P25 mode – 100-kHz PRF UWB interference.

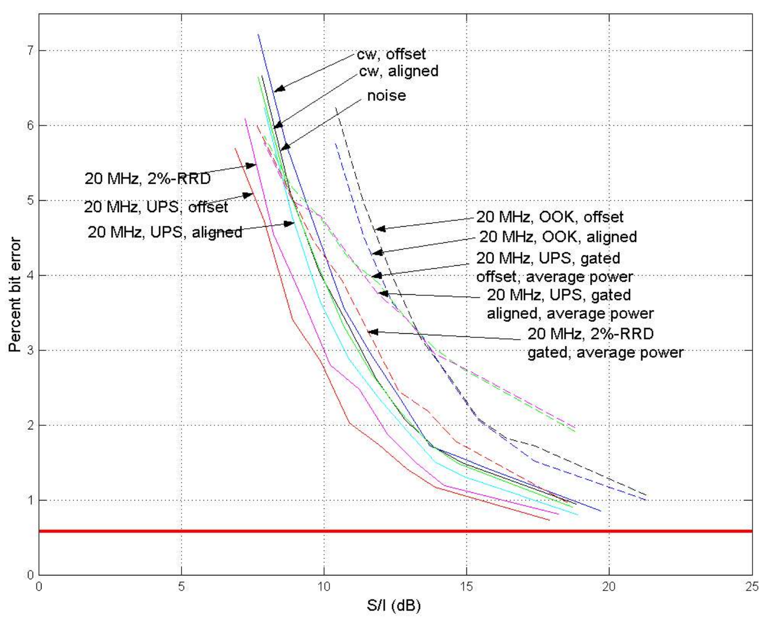

Figure 4.17. Percent bit-error versus S/I for Receiver B in P25 mode – 20-MHz PRF UWB interference.

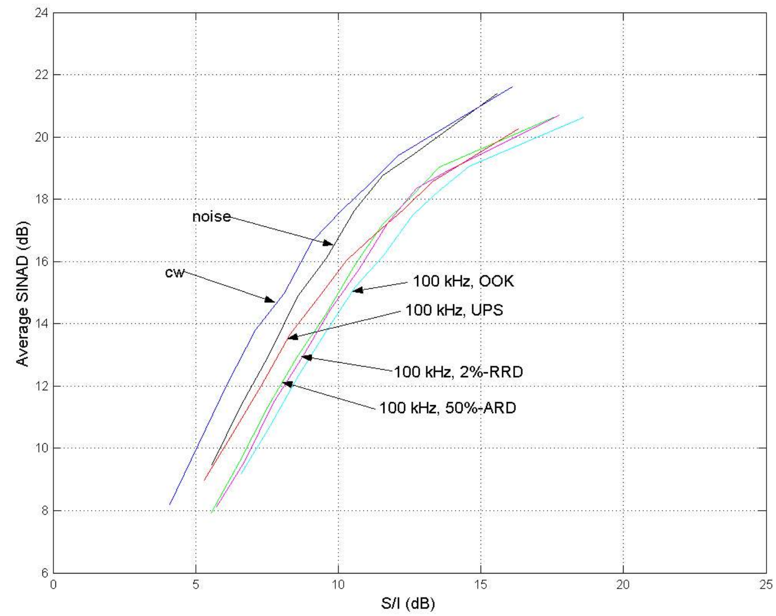

Figure 4.18. Average SINAD versus S/I for Receiver B in analog mode – 100-kHz PRF UWB interference.

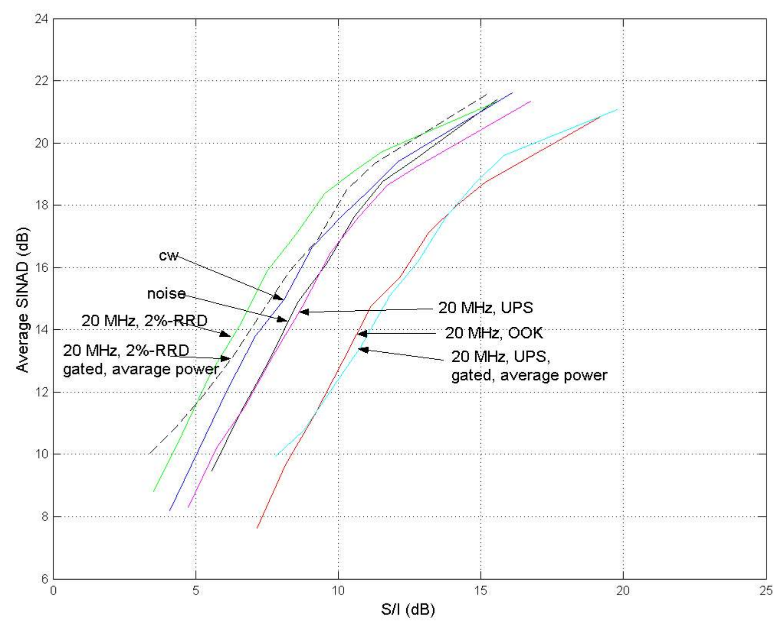

Figure 4.19. Average SINAD versus S/I for Receiver B in analog mode – 20-MHz PRF UWB interference.

4.2 Summary of Measurement Results

There are several trends in receiver response related to the various UWB characteristics such as pulse spacing, PRF, and gating. Figure 4.1 shows these trends (described below) to be remarkably similar among receivers, both in the digital and analog modes.

Because the PRF to receiver-bandwidth ratio for these measurements is always greater than 1, there is an overlapping of adjacent pulses after passing through the 12.5-MHz receiver passband; therefore, dithered signals, both RRD and ARD, have a Gaussian noise-like behavior in both the temporal and spectral domains when passed through the receiver passband transfer function. This is corroborated by Figure 4.1, which shows the in-band interference rejection ratios to be closely similar for noise, 50%-ARD, and 2%-RRD. The same trends can be noted in Figures 4.2, 4.3, 4.6, 4.7, 4.10, and 4.11.

Both the UPS and OOK signals have strong spectral lines. As such, it can be expected that UPS and OOK signals will, for the same 1-MBPD, have a more detrimental effect than dithered signals. For OOK signals used in these measurements, half the signal power is contained in a noise-like component. Therefore, for an equal 1-MBPD, OOK signals are not as likely to degrade receiver performance as the UPS signals. This is corroborated in both Figure 4.1 and Figures 4.2, 4.3, 4.6, 4.7, 4.10, and 4.11, which show UPS signals to be slightly more invasive than their OOK counterparts. Both are seen to be more invasive than dithered signals. For the 100-kHz case, there are 10 spectral lines within the 1-MHz band of power measurement, but only one of those spectral lines passes through the receiver filters. On the other hand, for CW signals and 20-MHz signals, there is only one spectral line within the 1-MHz band of power measurement, and all of the power in that spectral line passes through the receiver filters. Therefore, it is expected that, for signals with strong spectral lines to cause the same level of interference, there should be a 10-dB difference ($10 \log_{10}$[10-spectral-lines/1-spectral-line]) in the 1-MBPD between the 100-kHz signals and the 20-MHz (or CW) signals. This is validated by the same figures mentioned above.

Because the power of the gated signals is stated in terms of the gated-on time, it is expected that, for 20% gating, 7 dB more power is required of the gated signals to degrade the receivers to the same level as the non-gated counterparts. This is also validated for each case as evidenced by Figures 4.1, 4.2, 4.3, 4.6, 4.7, 4.10, and 4.11.

Figures 4.14 through 4.19 show that, when interference power is expressed in terms of RxBMPD, there is difference of only a few dB between signal types for the same level of performance. For the same RxBMPD, gated signals show slightly more performance degradation. When expressed in terms of signal-to-RxBMPD ratio (designated as S/I on the abscissa), reference sensitivity occurs at approximately 10 dB, with a variation of 2 to 5 dB on either side, depending upon the receiver and signal type.

5. CONCLUSION

As there are a variety of UWB signal types, there can be a multitude of receiver responses, depending upon the characteristics of the interfering signal and the method of power representation. For these measurements, a UWB signal space was generated by varying the parameters of pulse-spacing, PRF, and gating. The temporal and spectral characteristics of the interfering signal, as transformed by the receiver transfer function, are dependent on not only the nature of the transmitted interfering signal but also on the bandwidth and filter characteristics of the receiver.

The UWB signal, when altered by the receiver passband transfer function, can appear impulsive, Gaussian noise-like, sinusoidal, or a combination of the above. When a narrow pulse with a wide bandwidth is passed through a filter with a narrower bandwidth, the output approximates the impulse response of the filter, the result being that the output has a pulse width approximately equal to the reciprocal of the receiver bandwidth with an oscillation at the center frequency of the filter. As the pulses pass through the receiver filters, they become wider, and depending upon the PRF and extent of dithering, the pulses may overlap. It is the combination of these receiver characteristics and the nature of the interfering UWB signal (PRF, pulse spacing mode, and gating) that determines the properties of the signal as it passes through the signal processing chain of the receiver.

When passed through the receiver, the dithered and on-off-keyed UWB signals can take on impulsive or Gaussian noise-like characteristics, depending upon the PRF and the bandwidth of the receiver. Because the phase of the oscillation is dependent upon the time origin of the pulse, the phase for adjacent dithered pulses can be asynchronous. This can result in constructive and destructive summation of signal components for overlapping pulses, giving the appearance of Gaussian noise. OOK signals, while synchronous in phase for adjacent pulses, can take on a similar noise-like appearance when adjacent pulses overlap; however, OOK signals also have spectral lines, whereas dithered signals (depending upon the degree of dithering and the bandwidth and center frequency of the receiver) typically have no spectral lines. If the PRF of a UWB signal is sufficiently low (PRF to receiver bandwidth < 1), the pulses do not overlap, and therefore, the signal becomes impulsive in nature as it passes through the receiver.

Both OOK and UPS signals have spectral lines spaced at intervals equal to the PRF. Depending upon the bandwidth and center frequency of the receiver filters, one or more of these spectral lines can be passed to the receiver. If a single spectral line of a UPS signal is passed, the interference looks CW in nature. OOK is hybrid in nature, showing both spectral lines and noise-like spectral components. As more and more spectral lines are passed, the interference effects start to approach that of a Gaussian noise-like signal.

For the same 1-MBPD, experience has shown that many receivers incur the least interference from impulsive-type signals and the greatest interference from CW signals, with Gaussian noise lying somewhere in between [3] [4]. In this particular experiment, the receivers' bandwidths are narrow enough and the PRFs high enough that none of the generated signals were impulsive with regard to their effects. In both the 100-kHz case and the 20-MHz case, the pulses, as they are altered by the receiver processing chain, overlap; therefore, for both the 50%-ARD and the 2%-RRD signals, the interference effects are very similar to Gaussian noise. At the PRFs of 100 kHz and 20 MHz, both UPS and OOK signals have at most only a single spectral line that passes through the receiver filters. For this reason, the effects on the receiver are CW-like. For UPS, where the spectrum is only composed of lines, the effect on the receiver is identical to CW signals. For equal 1-MBPD, the 100-kHz UPS signals appear to be less harmful only because, for the 100-kHz case, there are 10 spectral lines within the 1-MHz band of power measurement, but only one of those spectral lines passes through the receiver filters. On the other hand, for the 20-MHz case, there is only one spectral line within the 1-MHz band of power measurement, and all of the power of that spectral line passes through the receiver filters. OOK signals, though they contain spectral lines, have some of the power distributed into Gaussian noise-like spectral components and therefore, for the same 1-MBPD, are not as interfering as the UPS counterpart.

Gated UWB signals, when measured in terms of their power during the gated on-time, require a decrease in power by a factor of $10 \log_{10}$ (*gating duty cycle*) to get a similar level of performance degradation as their non-gated counterparts. Therefore, when measured in terms of their average power, gated and non-gated signals show only a 1 to 2 dB difference in power for the same performance level.

When measured in terms of RxBMPD, most of the differences in signal degradation between interfering signal types disappear (impulsive signal type exempted since these were not measured). Even then, there are trends, with gated signals being slightly more invasive and signals with spectral lines being slightly less invasive than Gaussian noise-like signals.

6. ACKNOWLEDGMENTS

The authors of this report would like to recognize David Anderson and Ed Drocella of the NTIA Office of Spectrum Management for their contributions in the development of the original test plan and interpretation of the results.

Also recognized are John Vanderau for his expertise on Public Safety Radios, Jeanne Ratzloff for report editing and web site development, Margaret Luebs for editorial review, and Robert Achatz, Wayde Allen, Bob Matheson, and Steve Engelking for technical review.

This work was supported in whole by the Public Safety Wireless Network (PSWN) under the sponsorship of Robert E. Lee Jr. and Julio "Rick" Murphy, PSWN program managers for the Department of Justice and Department of Homeland Security, and James E. Downes, Acting Director, Wireless Programs Office, Department of Homeland Security.

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[1] *Notice of Proposed Rulemaking*, ET Dkt. 98-153 (rel. May 11, 2000), Federal Register, June 14, 2000, vol. 65, No. 115, pp. 37332 - 37335.

[2] W.A. Kissick, Ed., “The temporal and spectral characteristics of ultrawideband signals,” NTIA Report 01-383, Jan. 2001.

[3] J.R. Hoffman, M.G. Cotton, R.J. Achatz, R.N. Statz, and R.A. Dalke, “Measurements to determine potential interference to GPS receivers from ultrawideband transmission systems,” NTIA Report 01-384, Feb. 2001.

[4] J.R. Hoffman, M.G. Cotton, R.J. Achatz, and R.N. Statz, “Addendum to NTIA Report 01-384: Measurements to determine potential interference to GPS receivers from ultrawideband transmission systems,” NTIA Report 01-389, Sep. 2001.

[5] Project 25 Standards document TIA/EIA-102.CAAA, *Digital C4FM/CQPSK Transceiver Measurement Methods*

[6] Standards document TIA/EIA-603, *Land Mobile FM or PM Communications Equipment Measurement and Performance Standards.*

8. ACRONYMS

1-MBPD	1-MHz Bandwidth Power Density
ARD	Absolute referenced dithering
AWG	Arbitrary waveform generator
BER	Bit-error rate
BPF	Bandpass filter
BW	Bandwidth
C4FM	Four level frequency shift keyed
CW	Continuous wave
FCC	Federal Communications Commission
FM	Frequency modulation
ITS	Institute for Telecommunication Sciences
LMR	Land mobile radio
LPF	Low pass filter
LSNB	Line spreading null-to-null bandwidth – referring to the null spacing of the convolving sinc-squared function as a result of gating, where the null-to-null bandwidth is equal to 2 times the reciprocal of the gated-on time.
LSS	Line spread spacing – referring to the spacing between lines of the convolving sinc-squared function as a result of gating, where the distance between lines is equal to the reciprocal of the gating period.
MAPL	Minimum acceptable performance level
NPRM	Notice of proposed rulemaking
NTIA	National Telecommunications and Information Administration
OOK	On-off keying

P25	Project 25
PRF	Pulse repetition frequency
PRL	Pattern repetition lines – referring to spectral lines generated due to a repetition of the pulse pattern
RFI	Radio frequency interference
RRD	Relative referenced dithering
S/I	Signal-to-interference ratio
SINAD	Signal-plus-noise-plus-distortion to noise-plus-distortion ratio
SN	Spectral node – referring to a spectral feature due to the placement of the position of pulses within discrete bins
RxBMPD	Receiver Bandwidth Mean Power Density
UPS	Uniform pulse spacing
UWB	Ultrawideband

APPENDIX: CHARACTERISTICS OF GENERATED UWB SIGNALS

The following sections describe details of UWB signal generation.

A.1 Signal Description

Each of the UWB signals used in these measurements was generated using a Time Domain Corporation PG-2000 pulser, triggered by either an AWG or custom-designed 2%-RRD trigger circuit.

Table A-1 lists parameters for each of the 17 UWB signals used for these measurements.

Table A-1. Characteristics of Generated UWB Signals

PRF (MHz)	Pulse Spacing Mode	Duty Cycle (%)	PRL[1] Spacing (kHz)	Spectral Line Placement [2] (MHz)	LSNB [3] (Hz)	LSS [4] (Hz)	Nearest SN to L1 [5] (MHz)
0.1	UPS	100	N/A	138.000506	N/A	N/A	N/A
0.1	UPS	100	N/A	137.999862	N/A	N/A	N/A
0.1	UPS	20	N/A	138.000506	500	50	N/A
0.1	UPS	20	N/A	137.999862	500	50	N/A
20	UPS	100	N/A	138.000506	N/A	N/A	N/A
20	UPS	100	N/A	137.999862	N/A	N/A	N/A
20	UPS	20	N/A	138.000506	500	50	N/A
20	UPS	20	N/A	137.999862	500	50	N/A
0.1	OOK	100	0.059	138.000506	N/A	N/A	N/A
0.1	OOK	100	0.059	137.999862	N/A	N/A	N/A
20	OOK	100	0.357	138.000506	N/A	N/A	N/A
20	OOK	100	0.357	137.999862	N/A	N/A	N/A
0.1	50%-ARD	100	0.098	N/A	N/A	N/A	119.1
0.1	50%-ARD	20	0.098	N/A	500	50	119.1
0.1	2%-RRD	100	0.25	N/A	N/A	N/A	95.0
20	2%-RRD	100	N/A	N/A	N/A	N/A	N/A

Con't Table A-1. Characteristics of Generated UWB Signals

PRF (MHz)	Pulse Spacing Mode	Duty Cycle (%)	PRL[1] Spacing (kHz)	Spectral Line Placement [2] (MHz)	LSNB [3] (Hz)	LSS [4] (Hz)	Nearest SN to L1 [5] (MHz)
20	2%-RRD	20	N/A	N/A	N/A	N/A	N/A

1 Pattern Repetition Lines (PRL) refer to spectral lines generated due to a repetition of the pulse pattern. (See Section A.2 for a complete discussion.)

2 Lines due to the pulse repetition period are spaced at intervals equal to the reciprocal of PRF, but for each UWB with these spectral lines, the PRF is adjusted slightly so that one of the lines occurs at 1575.570571 MHz.

3 Line Spreading Null-to-null Bandwidth (LSNB) refers to the null spacing of the convolving sinc-squared function as a result of gating, where the null-to-null bandwidth is equal to 2 times the reciprocal of the gated-on time. (See Section 3.1.2 for a complete discussion.)

4 Line Spread Spacing (LSS) refers to the spacing between lines of the convolving sinc-squared function as a result of gating, where the distance between lines is equal to the reciprocal of the gating period. (See Section 3.1.2 for a complete discussion.)

5 Spectral Node (SN) refers to a spectral feature due to the placement of the position of pulses within discrete bins. (See Section A.2 for a complete discussion.)

A.2 Residual Spectral Effects due to Signal Generation

Because the pattern of pulse spacing, whether it be OOK or dithering, is stored in the memory of an AWG and because that memory has limits with regard to size, the same pattern has to be repeated at periodic intervals. This pattern repetition results in signal power being gathered up into spectral lines with a spacing equal to the reciprocal of the period of the pattern. For those UWB cases where we would expect real world signals to have no pattern repetition, the pattern is made as long as possible so that the spectral lines are spaced very close together, and therefore, have negligible impact on the receiver. For purposes of brevity, we call these spectral lines Pattern Repetition Lines (PRL).

Also because of the limitations of memory size and sample rates of the AWG, the location of pulses (within the context of dithering) has to be confined to a limited number of discrete time bins. This is illustrated in Figure A-1 for the case of 50% clock-referenced dithering, in which the pulse position can be assigned to any of 19 possible discrete positions within the first 50% of the interval between reference clock periods (t is the size of the bins, in units of time). As opposed to a continuum of possible pulse positions, this discrete binning results in some additional spectral features worth noting. Figure A-2 demonstrates what we

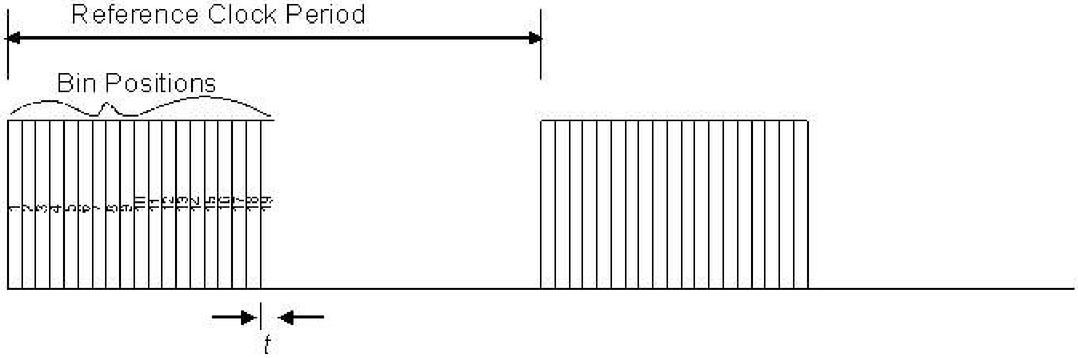

Figure A-1. Discrete binning of pulse position for clock referenced dithering.

have described as a spectral node (SN), in which there is a depression in the spectral noise and the emergence of spectral lines. The spacing of these spectral nodes is directly related to the bin size *t*, where the distance between spectral nodes is 1/*t*. This phenomenon is described in greater detail in Appendix D (Theoretical Analysis of UWB Signals Using Binary Pulse-modulation and Fixed Time-base Dither) of [3]. For these measurements, efforts were specifically made to place these spectral nodes in a location other than the 138-MHz band.

The custom built 2%-RRD circuit is analog, and therefore signals generated using this circuit do not have PRLs or SNs characteristic of signals generated digitally with an AWG.

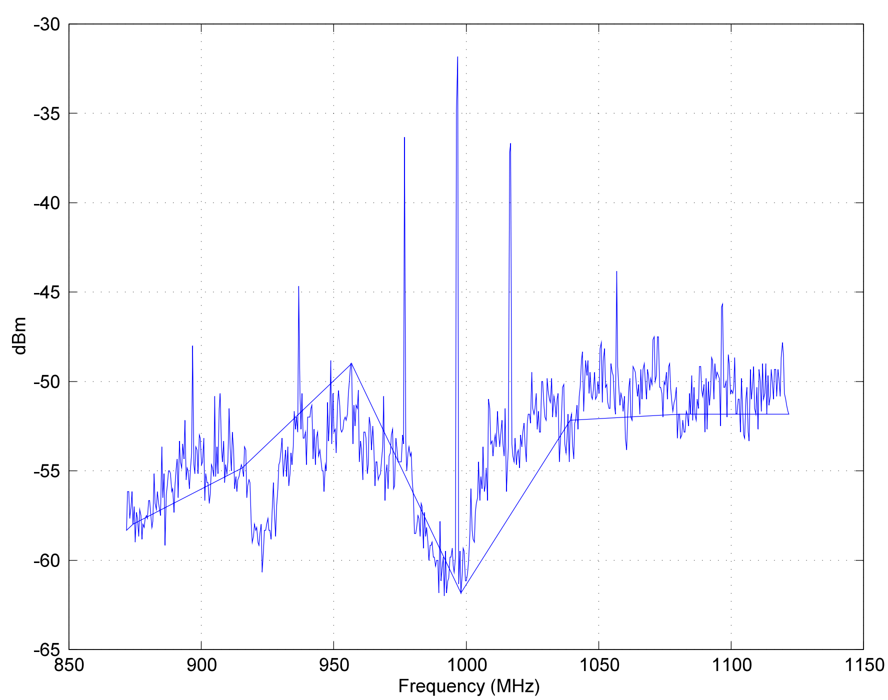

Figure A.3. Spectral lines due to discrete binning of pulse position.