A PROGRAMMABLE ULTRA WIDEBAND SIGNAL GENERATOR FOR ELECTROMAGNETIC SUSCEPTIBILITY TESTING

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ABSTRACT

Under Phase I of the Defense Advanced Research Projects Agency (DARPA) Networking in Extreme Environments (*NETEX*) initiative, Multispectral Solutions, Inc. (MSSI) was tasked with the development of a general purpose, ultra wideband hardware simulator capable of reproducing a wide variety of ultra wideband (UWB) waveforms. The simulator, with UWB outputs from baseband through millimeter wave, was to be used for the purpose of electromagnetic susceptibility testing of legacy military radio, radar and positioning systems. The ultimate goal of this portion of the Phase I program was the quantitative determination of those UWB parameters (e.g., frequency, power, pulse rate, pulse shape, dithering, etc.) which had the least impact on the operational performance of legacy designs. This paper describes the development of the MSSI NETEX UWB simulator (BFP1000).

1. INTRODUCTION

DARPA's program on Networking in Extreme Environments was initiated to "enable the delivery of systems that exploit the unique benefits of the UWB physical layer to provide robust communications in complex terrain" [1]. Phase I of this effort was designed to gain a better understanding of the effects of UWB system operation on existing, militarily-critical, narrowband and wideband systems. While some preliminary results on electromagnetic compatibility of UWB waveforms were available from recent National Telecommunications and Information Administration (NTIA) UWB testing [2-5], these tests considered only a very small subset of Government-critical systems, primarily GPS and certain search and tracking radar systems.

In addition, the NTIA tests were restricted to an evaluation of system performance in the presence of UWB emissions operating at the proposed FCC Part 15 limits (more specifically, at the -41.25 dBm/MHz average power density level), and did not enable a determination of the worst case emission levels for a given legacy system configuration.

In Phase I, MSSI was tasked with the design, development, fabrication and acceptance testing of 20 UWB signal generators – 16 providing baseband pulse and filtered RF outputs from 20 MHz through 4 GHz; and four units providing baseband output and filtered RF through 16 GHz for low millimeter wave testing. The UWB generators were to be used both for conducted (i.e., cabled) testing as well as for radiated emission testing; the latter to be performed with the use of calibrated wideband antennas.

During the Phase I effort, a total of seventeen different military receivers, operating in a total of thirty-nine modes at a total of sixty-five fixed frequencies and five frequency hop-sets from 30 MHz to 16 GHz, were tested by DARPA [6]. Altogether over 1,600 individual tests were conducted over a period of five months. The effort included (a) identifying those UWB waveforms that would result in electromagnetic compatibility with legacy systems; (b) identifying those UWB waveforms that would most likely cause electromagnetic interference (EMI) to legacy systems; (c) defining UWB thresholds for EMI; and (d) comparing UWB EMI levels to additive white Gaussian noise (AWGN) levels for an equivalent EMI impact.

Specific receiver systems tested (cf. Table 1 below) included communications, aircraft guidance systems, and radars. Each of these systems had been previously tested for electromagnetic interference (EMI) susceptibility in accordance with the procedures of MIL-STD-462/462D/461E [7], and for susceptibility levels specified in MIL-STD-461 (current at the time of testing). EMI testing with the UWB simulators was performed at the Electromagnetic Environmental Effects Division of the Naval Air Warfare Center Aircraft Division (NAWCAD), Patuxent River, Maryland.

2. UWB SIGNAL GENERATOR DESIGN

The UWB signal generator developed under this Phase I initiative, BFP1000 (cf. Figure 1), emulates a wide range of UWB characteristics. The units produce both a fixed, baseband pulse (nominally 250 ps in duration) and short pulse RF from 20 MHz through 16 GHz, the latter achieved through the use of passband filtering and subsequent amplification of the baseband pulses.

Table 1. Military Receivers Tested

Nomenclature	Function
ARN-147	Commercial Instrument Landing System
ARC-210	VHF/UHF Communication System
APN-194(V)	Radar Altimeter
APX-100	Identification Friend or Foe (IFF) Transponder
ARA-63	Aircraft Carrier Landing System (CILS)
ARN-118	Tactical Air Navigation (TACAN)
PRC-117F	VHF/UHF Communication System
UPX-38	IFF Interrogator
EPLRS	Enhanced Position Location Reporting System
JTIDS	Joint Tactical Information Distribution System
SPN-35	Carrier Approach Control Radar
SPN-43	Carrier Marshal Radar
ARQ-44	Light Airborne Multipurpose System (LAMPS) MK III
SRQ-4	Radio Terminal Set (LAMPS)
SLQ-32	Shipboard Electronic Warfare System
AMC-06	SHF SATCOM – Ku-band Transceiver
GPS	Global Positioning System

Figure 1. MSSI UWB Signal Generator (BFP1000)

A system level block diagram of the BFP1000 is shown in Figure 2. The signal generator design is straightforward. A Baseband Module, with harmonic content to millimeter wave, is used either directly as an impulse excitation, or after subsequent bandpass filtering at a desired nominal carrier frequency and bandwidth. Further amplification is provided to achieve peak signal levels of +30 dBm, as measured on a time domain sampling oscilloscope so as to obtain an accurate measure of full bandwidth peak power. A microcontroller and Direct Digital Synthesizer (DDS) are used to produce a wide variety of user-selectable pulse repetition frequencies and pulse patterns.

The Baseband Module actually produces three basic pulse shapes (cf. Figures 3 and 4) – a positive-going double exponential pulse, a negative-going double exponential pulse[1] and a Gaussian monocycle. Each polarity of the double exponential pulse is separately triggerable, permitting the generation of arbitrarily spaced pulse doublets (e.g., for emulation of biphase modulations); while the Gaussian monocycle is obtained from a simple transmission line transformation of the positive double exponential (i.e., $^1/_4\lambda$ shorted stub adjusted along a coaxial transmission line to provide the sum of the original pulse and its delayed, inverted replica). The maximum usable pulse repetition frequency (PRF) for the Baseband Module was designed to be in excess of 100 Mpps, permitting EMI evaluation over a wide range of pulse parameters.

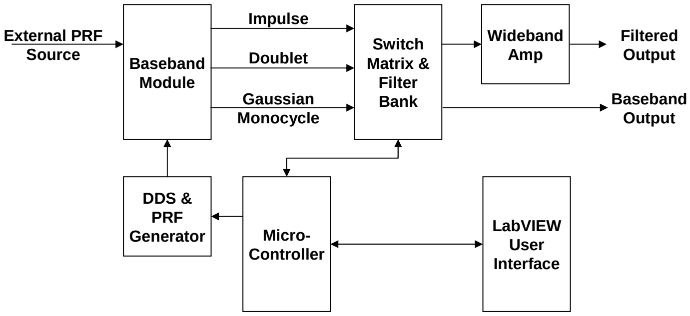
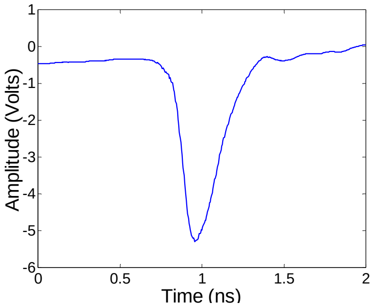


Figure 2. BFP1001 UWB Signal Generator System-Level Block Diagram



Rise Time: 269 ps.
Fall Time: 127 ps.
Width (rms): 245 ps.

Figure 3. Baseband Pulse Output (Negative-going double exponential)

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[1] The double exponential pulse has an extremely fast exponential rise (fall) time of approximately 125 ps; a somewhat slower exponential decay (rise) – typically 250 ps to the 1/e value; and an RMS duration of approximately 250 ps.

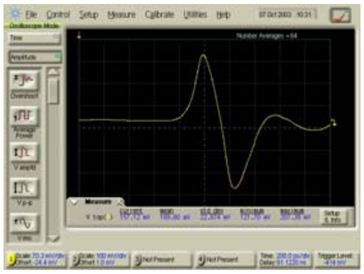

Figure 4. Gaussian Monocycle Output (200 ps/div)

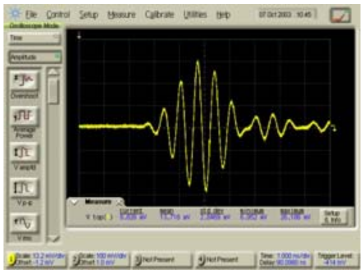

Figure 5. Filtered (L-band) Baseband Output (1 ns/div)

The generated UWB pulses – double exponential p(t), Gaussian monocycle g(t) and filtered burst f(t) – have the approximate mathematical relationships given below:

$$p(t) = \frac{t}{\alpha}\exp\left(1 - {t}/{\alpha}\right)u_{-1}(t)$$

$$g(t) = \frac{t}{\alpha}\exp\left(-\left[{t}/{\alpha}\right]^2\right)$$

$$f(t) = h_{LP}(t)\cos(\omega_0 t)u_{-1}(t)$$

where $u_{-1}(t)$ is the unit step function, α is a parameter which affects the resultant pulsewidth, ω_0 is the filter center frequency and $h_{LP}(t)$ its lowpass equivalent.

The measured baseband pulse power spectral density is also illustrated in Figure 6 below.

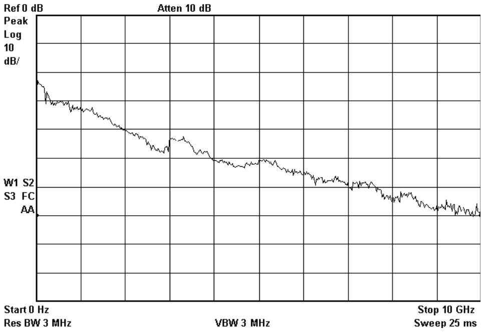

Figure 6. Baseband Pulse Power Spectral Density

The Baseband Module, which utilizes microwave step recovery diodes (SRDs) for signal generation, has usable RF output well into the low millimeter wave bands. As such, it is a useful tool for the impulse characterization of UWB systems over the full range of FCC Part 15 Subpart F (UWB) compliance limits (e.g., 3.1-10.6 GHz). Figure 7 illustrates a commercial version of the Baseband Module which was developed as a commercial offshoot of this program.

Figure 7. TFP1001 Baseband Module

An internal microprocessor (22 MHz Rabbit 2000) and arbitrary waveform (PRF) generator (DDS and custom field programmable gate array) were provided to enable the user to generate an extensive variety of UWB waveforms; including constant PRF waveforms from 1pps to 100 Mpps; randomly jittered PRF up to ±100% jitter; patterned PRFs and packet burst transmissions (user definable); and random pulse position modulation (PPM).

The PRF-modulated baseband waveforms were then applied to an RF switch matrix and filter bank which permitted either the direct output of the baseband excitation, or the subsequent filtering and amplification of the baseband pulse to yield a short-pulse modulated bandpass (filtered) RF output (cf. Figure 5). For filtered UWB RF emissions, bands were chosen so as to overlap existing legacy system operating ranges; while an option was also provided for user-definable plug-in filters (Cf. Figure 8).

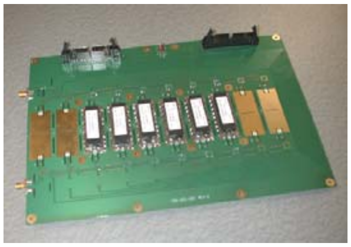

Figure 8. BFP1000 Switchable Filter Bank

The upper frequency of operation for the UWB signal generator was approximately 16 GHz; essentially limited by the frequency response of the Baseband Module, RF switching and cabling losses. Wideband RF amplification was provided to achieve full bandwidth power levels in excess of +30 dBm. Figure 9 illustrates the frequency occupancy of the BFP1000 baseband output for a number of PRFs as measured in a 3 MHz resolution bandwidth.

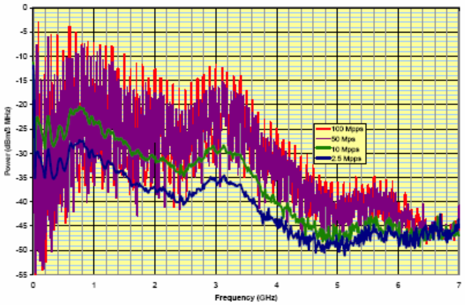

Figure 9. PRF Modulated Baseband Output

One limitation of the BFP1000 internal PRF generator was the production of distinct phase-noise sidebands at very high multiples of the PRF (cf. Figure 10). At very high harmonics, these sidebands dominated the spectrum between spectral lines of the desired PRF, causing the spectrum to become more noise-like than discrete. This is to be expected since, although the DDS utilized a very low distortion D-to-A converter, the phase noise increases directly with increasing clock multiple. To remedy this, an external arbitrary waveform generator (Tektronix AWG series) was used to provide a much cleaner reference for low PRF waveforms.

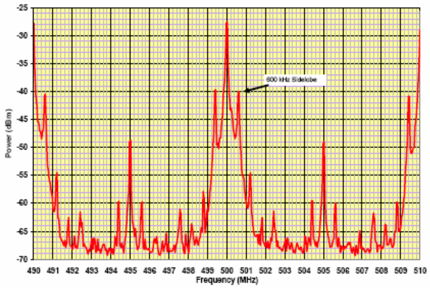

Figure 10. Sidebands in UWB Clock Harmonics of 10 Mpps Pulse about Fiftieth Harmonic [6, Fig.3]

In addition to the UWB generators, a set of commercially available, calibrated reference antennas (Figure 10) were also provided to DARPA for radiated measurements.

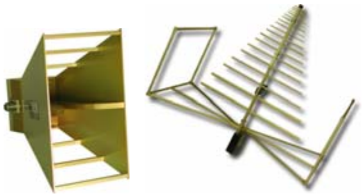

Figure 11. AH Systems, Inc. Wideband Calibrated Antennas Used for Radiated Tests

Left: SAS-571 Double Ridge Guide Horn (0.7-18 GHz)
Right: SAS-521-2 Bilogical Hybrid Biconical/Log Periodic (0.025-2.0 GHz)

3. EMI Test Waveforms

A set of seven basic UWB Test Waveforms (TW) were generated with the BFP1000:

TW1 – PRF was set to the maximum value available from the UWB pulse generator that resulted in the fundamental, or an harmonic, of the PRF falling within the receiver RF passband. The PRF was unmodulated.

TW2 – The base PRF of TW2 was similar to TW1 except that TW2 was dithered in a manner to attempt to partially fill the receiver passband. TW2 was dithered by the largest available percentage which would not cause the occupied bandwidth of the dithered signal to exceed the victim receiver bandwidth (RXBW).

TW3 – The base PRF of TW3 was selected to be equal to the victim RXBW (full bandwidth occupancy).

TW4 – The base PRF of TW4 was again selected to be the victim RXBW. The TW4 modulation was selected, on a case-by-case basis, to cause the most interference to the victim receiver. Three different modulations were used: (i) a swept Frequency Modulated (FM) PRF at the victim RXBW; (2) an on-off keyed (OOK) waveform with a symbol rate equal to the victim RXBW and a continuous stream of alternating 1s and 0s; and (3) an OOK waveform with a symbol rate equal to the victim RXBW and a continuous stream of random 1s and 0s.

TW5 – The PRF of TW5 was one tenth of the victim RXBW. TW5 was unmodulated.

TW6 – The PRF of TW6 was ten times the victim RXBW. TW6 was unmodulated.

TW7 – The PRF of TW7 was one hundredth of the RXBW. TW7 was unmodulated.

A LabVIEW graphical user interface (cf. Figure 121) was developed to provide a simple method for changing test waveform parameters.

PRF (MHz) 25.0000
Data Pattern all ones
Operational Mode positive OOK
Packet Size 4096
COM Port Select COM2
Unit select 7

Figure 12. LabVIEW Interface for UWB Generator

A summary of the results of EMI testing on the military legacy systems can be found in [6]; however, full test reports are classified and can only be obtained through appropriate channels. One interesting result, however, of the EMI testing was the creation of a Spectral Mask (cf. Figure 13) which showed the average power level, reference to the victim receiver input and adjusted for a 1 kHz RXBW, which resulted in the onset of UWB interference to each legacy military system. This Spectral Mask was used to determine appropriate operational frequencies and power levels for coexistence of UWB radios with the legacy systems.

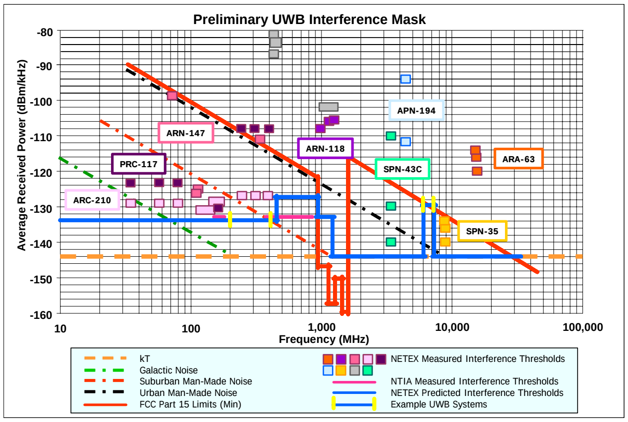

Figure 13. UWB Interference Mask

4. CONCLUSIONS

A generic UWB signal generator was commissioned by DARPA for the purpose of gaining a better understanding of the effects of UWB waveform parameters on legacy military systems. The BFP1000 was designed for this purpose, and permitted the quantitative determination of those UWB parameters (e.g., frequency, power, pulse rate, pulse shape, dithering, etc.) which had the least impact on the operational performance of these legacy designs. Data obtained from extensive testing with the BFP1000 on 17 legacy systems enabled the development of a spectral mask that represents the maximum permissible UWB signal level, below which electromagnetic interference is not an issue for systems operating at the specified frequencies. In its Final Report [6], DARPA concluded:

(i) For most combinations of UWB waveforms and receivers, the EMI impact was related to the average UWB signal in the narrowest passband of the receiver;

(ii) For most waveform and receiver combinations, UWB signals will cause about the same affect as white noise that is at an equivalent level;

(iii) For high PRFs, there is significant space between spectral lines where there is very little or no interference; and,

(iv) Very low PRFs (equal to or less than RXBW/100) are unlikely to cause interference at any frequency.

The tests with the BFP1000 resulted in the identification of a broad range of UWB operating parameters that will support militarily useful functions (e.g., sensor and networked communication systems) that can coexist with legacy military systems and not cause undesired EMI which would impact their operation.

Finally, while the microcontroller and Direct Digital Synthesizer within the BFP1000 permitted rapid reconfiguration of test waveforms with almost unlimited variability, the phase noise on the DDS-derived clock resulted in spurious sidebands at high multiples of the PRF, limiting the performance of the unit at low PRFs. For these cases, the dual outputs of the internal Baseband Module was directly controlled with an external arbitrary waveform generator, resulting in significantly reduced sideband energies. In fact, the Baseband Module was so useful that it has become a standard commercial product, TFP1001, in use by a number of US and non-US government agencies for the evaluation of UWB interference.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] DARPA Networking in Extreme Environments, Industry Day presentations, 7 April 2003.

[2] Kissick, W.A., editor, "The Temporal and Spectral Characteristics of Ultrawideband Signals," NTIA Report 01-383, January 2001.

[3] Hoffman, R.J., 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, February 2001.

[4] Brunson, L.K. et al., "Assessment of Compatibility Between Ultrawideband Devices and Selected Federal Systems," NTIA Special Publication 01-43, January 2001.

[5] Anderson, D.S., E.F. Drocella, S.K. Jones and M.A. Settle, "Assessment of Compatibility between Ultrawideband (UWB) Systems and Global Positioning Systems (GPS) Receivers", NTIA Special Publication 01-45, February 2001.

[6] “Networking in Extreme Environments – UWB Parameters for EMC Coexistence with Legacy Systems,” Final Report, Defense Advanced Research Projects Agency, 31 June 2003.

[7] “MIL-STD-461E, Requirements for the Control of Electromagnetic Interference and Characteristics of Subsystems and Equipment,” Department of Defense Interface Standard, 20 August 1999. (See, for example, assist.daps.dla.mil/docimages/0001/77/28/M461E.PD6.)