THE IMPLICATIONS OF .8 GHZ TO 3 GHZ TERRESTRIAL BAND CHARACTERIZATION ON VEHICULAR SDR DESIGN

Andrew Macdonald (GM R&D, Warren, MI, USA; andrew.macdonald@gm.com)
John Liu (Wayne State University, Detroit, MI, USA; jliu@eng.wayne.edu)

ABSTRACT

Automobile manufacturers are intrigued by SDRs. Long design cycles and long service lives make vehicles particularly vulnerable to obsolescence. This is particularly evident when the devices and services of vehicular and consumer electronics overlap. A recent example is the disabling of older OnStar Telematics modules when analog cellular service was discontinued in the US. This inconvenienced OnStar customers and financially burdened OnStar and GM. An SDR that could adapt to changes in existing protocols and support the introduction of new protocols (and associated services) would go a long way to bridging the vehicular and consumer electronics divide.

The most significant deterrent to the introduction of vehicular SDRs has been the cost-performance curve of ADCs. A front-end, with enough dynamic range to limit outages to acceptable levels, has been too expensive for automotive applications. As the price of ICs has come down and alternate front-end designs have shown promise, SDRs have become real contenders in the automotive space. A more careful and exacting analysis of SDR performance, in vehicular environments, is now required.

1. INTRODUCTION

Besides a wideband front-end's bandwidth, its most important quality is its dynamic range. If an SDR is designed to operate between 1 GHz and 2 GHz, what would be the required dynamic range? It would depend on the received power statistics of all signals in the band, the amplitude of smallest signal of interest (typically a narrowband signal such as GSM), and the acceptable outage probabilities for all in-band signals to be demodulated. What is missing, when this sort of analysis is attempted, is a characterization of the simultaneous received power levels for all in-band signals. Previous surveys, such as the one performed by Sanders, Ramsey, and Lawrence in San Diego[1], were focused on longer term averages and cannot be used in this analysis.

The goal of the research is to characterize the .8 GHz to 3 GHz band well enough to predict the relationship between front-end dynamic range and outage probability for the types of wireless services likely to be deployed in SDR equipped vehicles.

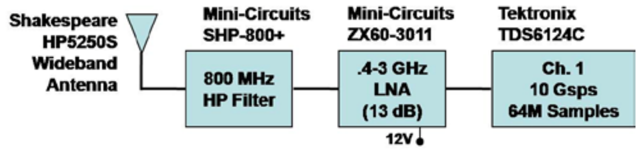

Figure 1: Data Collection Components

Figure 2: Data Collection Vehicle

Figure 3: Antenna Platform

To achieve this, 10 Gsps measurements were made at 69 locations in the Detroit, MI metropolitan area. A spectral analysis of these waveforms was performed and frequency-based patterns observed. This information was then used to develop front-end filtering strategies and estimate dynamic range requirements.

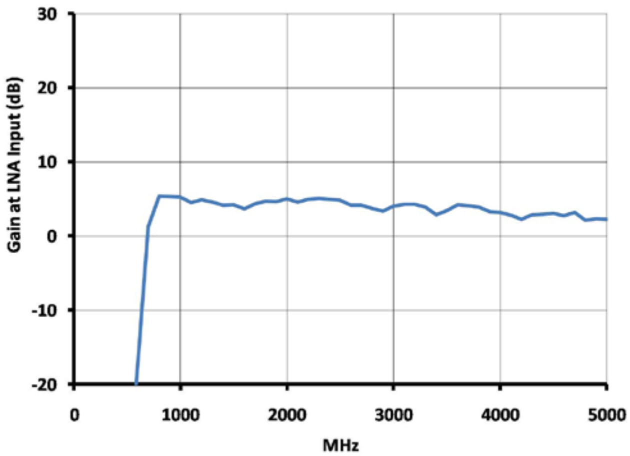

Figure 4: Flatness of Antenna, Cable, and High-Pass Filter

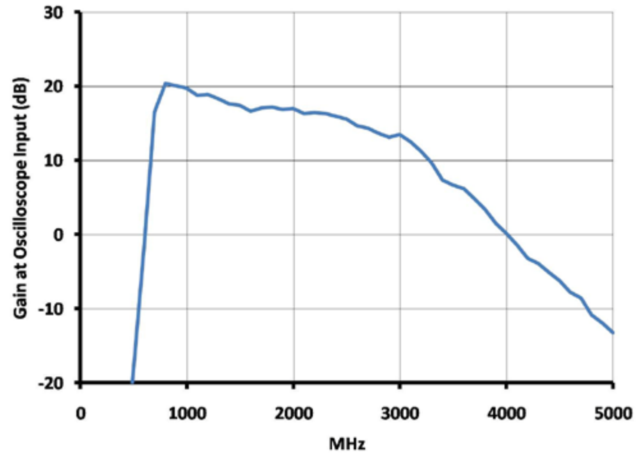

Figure 5: Antenna to Scope Input Gain Variations

2. DATA COLLECTION EQUIPMENT

A representation of the equipment used for data collection is shown in Figure 1. The wideband signal is received via a Shakespeare HP5250S antenna. This antenna was chosen for its flat response over the band of interest for elevations consistent with terrestrial communications [2]. The antenna has relatively flat gain across the .8 to 3 GHz band; averaging about 6 dBi. The instrumented vehicle and a close-up of the antenna platform are shown in Figure 2 and Figure 3 respectively

Since the front-end of the oscilloscope lacked the required sensitivity, an LNA was introduced to lower the noise floor of the data collected by the oscilloscope. It was chosen for its relatively flat gain of roughly 13 dB and for its nominal noise figure of 1.5 dB.

Protecting the LNA from saturation was one design consideration. Strong TV-band and radio-band signals were of particular concern. This issue was addressed by introducing an inline high-pass filter after the antenna, but before the LNA. It provides enough attenuation of signals between 0 and 800 MHz to prevent LNA saturation during the data collection process.

The availability of equipment able to sample at rates of 10 Gsps and above is limited. The Tektronix TDS-6124C can capture waveforms at rates up to 40 Gsps [3]. This oscilloscope was outfitted with additional memory; increasing its storage capability to 64 million 8-bit samples. At the sampling rate of 10 GHz used here, a maximum of 6.4 milliseconds of the waveform can be recorded.

3. CALIBRATION AND LIMITATIONS

This study was not intended to focus on sub-dB precision. Rather, it represents an attempt to establish a statistical understanding of the terrestrial (vehicular) environment over the range of .8 GHz to 3 GHz. Inaccuracies of a few dB are unlikely to alter the statistics derived from the data in any meaningful way.

Still, an attempt was made to limit the effects of the imperfections in the data collection process. These effects can be categorized as follows:

1) Variations in thermal noise effects due to gain variations at the LNA input.
2) Reduction in effective oscilloscope dynamic range due to gain variations at the oscilloscope input (uncompensated)
3) Inaccuracies in statistics derived from sampled data due to frequency dependent gain variations (compensated)

3.1. Thermal Noise Effects

A significant variation in gain (at the LNA input) can introduce unwanted thermal noise after the LNA. A flat in-band gain insures a more uniform thermal noise effect after the LNA and subsequent post processing gain adjustments. Although the quantization noise of the oscilloscope dominates, the flatness of the antenna, cable loss, and high-pass filter were considered. The nominal gain associated with the aggregate of these components is shown in Figure 4. The figure shows a relatively small gain variation of about 2 dB across the band of interest (.8 GHz to 3 GHz).

3.2. Oscilloscope Dynamic Range Reduction

A significant frequency-dependent gain variation, as seen at the input of the scope, can reduce effective band-wide dynamic range. An over-emphasis in one part of the band will reduce the effective dynamic range of the scope at other lower-gain parts of the band. A variation across the desired band of 20 dB could significantly reduce the effective dynamic range. Figure 5 shows the nominal gain variations

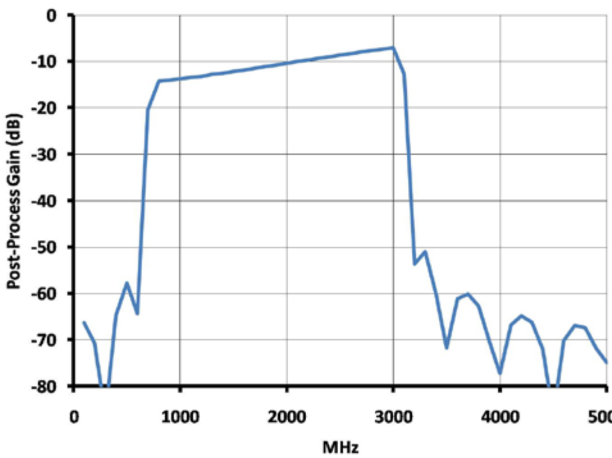

Figure 6: Post Processing Compensation Gain

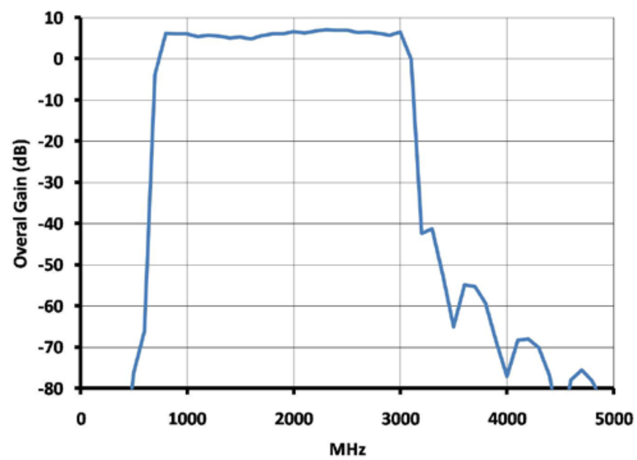

Figure 7: Data Collection Gain with Post Processing

at the oscilloscope input. It shows a relatively modest variation of about 7dB between .8 GHz and 3 GHz.

A second source of oscilloscope dynamic range reduction is the admittance of strong signals outside the .8 GHz to 3 GHz band. Figure 5 also shows the out-of-band rejection performance of the wideband equipment. Although the high-pass filter's roll-off is relatively sharp below 800 MHz, strong TV band signals in the 700 MHz band can express considerable power at the oscilloscope's input. This was observed at several of the sites, but not to an extent that dynamic range was significantly compromised.

3.3. Gain Compensation and Scaling

All thermal noise and dynamic range issues aside, in-band flatness plays a critical role in accurately evaluating the statistics of the received signals. Each of the 69 data sets was post-processed using a filter with the gain characteristics shown in Figure 6. This bandpass filter also has sharp skirts to remove most of the power from out-of band signals. The resulting in-band flatness is shown in Figure 7. Within the .8 GHz to 3 GHz band, the nominal gain varies less than 2 dB.

The filter shown in Figure 6 was also used for scaling. The data collected for this study will also be used in receiver studies for wireless protocols such as GSM and WiFi. A convenience in this regard is to have waveforms consistent with the output of a realistic antenna. For terrestrial wideband signal reception, a gain of 6 dBi is reasonable. The appropriate scaling factor was included in the filter such that the overall gain (Figure 7) is consistent with the output of a 6 dBi antenna.

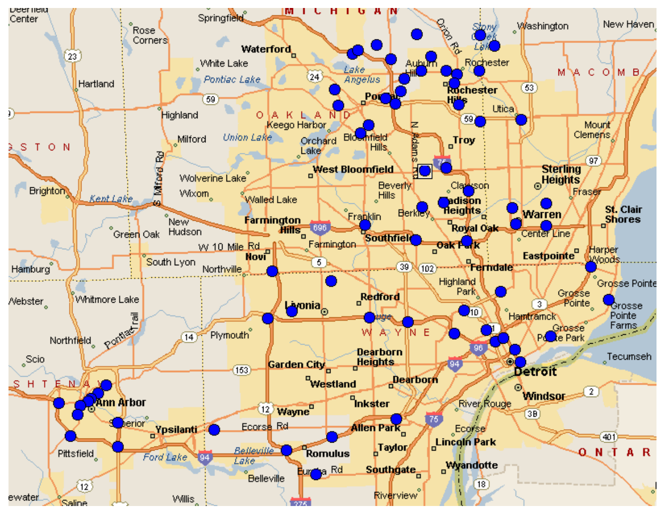

Figure 8: Data Collection Sites

4. SITE SELECTION

For this data collection effort, GM committed the resources to evaluate 50 - 100 sites in the Detroit, MI area. Clearly, 50 is a suboptimal site count for the intended purpose; developing of a statistical basis for predicting outage probabilities. Still, it can provide a rough understanding of performance issues and will give insight into vehicle-centric SDR design.

Given the limited number of locations, site selection was critical. If, for example, outage probability is of ultimate interest, the site density should be proportional to vehicle density. If, on the other hand, receive design insight is desired, the density of sites might be skewed toward sites with unusual characteristics (proximity to radar installations, TV stations, XM and Sirius ground repeaters, etc.). The site selection used for this study is a compromise between the two.

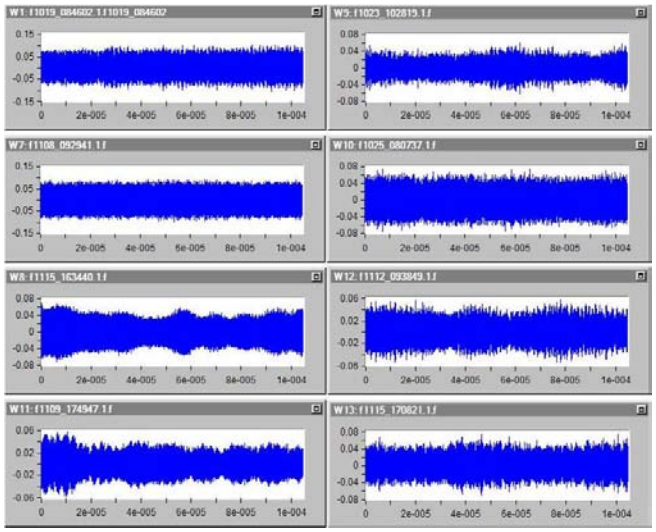

Figure 9: Eight Strongest Waveforms

From Figure 8 it can be seen that the sites were concentrated along the heavily traveled roads. Care was taken to include a few sites that could prove problematic to a wideband receiver. Two sites were chosen near Detroit Metro Airport to pick up any in-band signals from radar systems and aeronautical communications. One site, in Southfield, Michigan, was chosen for its close proximity to a number of TV towers.

5. CONCENTRATION OF POWER

For vehicular applications of wideband receivers, the worst-case signals to receive are those with the lowest average voltage.   This typically occurs when the required demodulation SNR is low and the signal's bandwidth is narrow. A GSM signal, for example, can be received at approximately $2x10^{-6}$ Volts RMS (into 50 Ohms). The maximum wideband receiver requirement occurs when a small signal, such as the GSM signal above, must be received in the presence of the largest aggregate signal. One way to better understand this worst-case stress on a wideband receiver is to analyze the cases where the aggregate signal is large. By doing so, an engineering decision can be made to exclude specific bands in order to reduce the overall dynamic range requirement; a tradeoff between flexibility and dynamic range requirements.

Figure 9 provides a graphical representation (in the time domain) of the strongest aggregate signals; each from a different site. The large power levels produced at these sites were typically the result of one or two strong signals.

One way to search for a pattern in these high power signals is to look at their spectra. A more direct way to accomplish this is to look at the spectrum for the sum of these signals. This spectrum, shown in Figure 10, is not particularly interesting. If the cumulative power is graphed

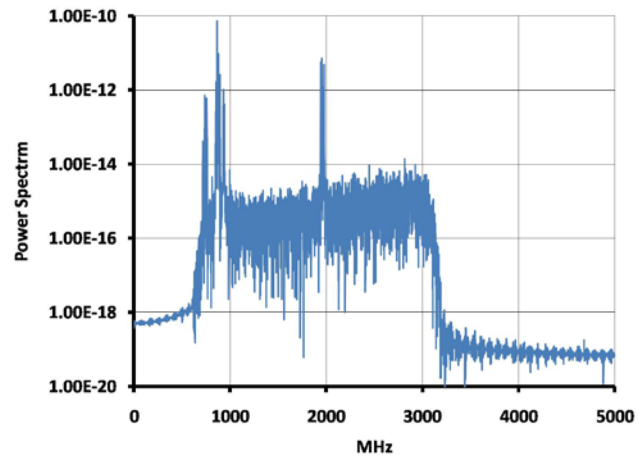

Figure 10: Power Spectrum of 8 Strongest Waveforms

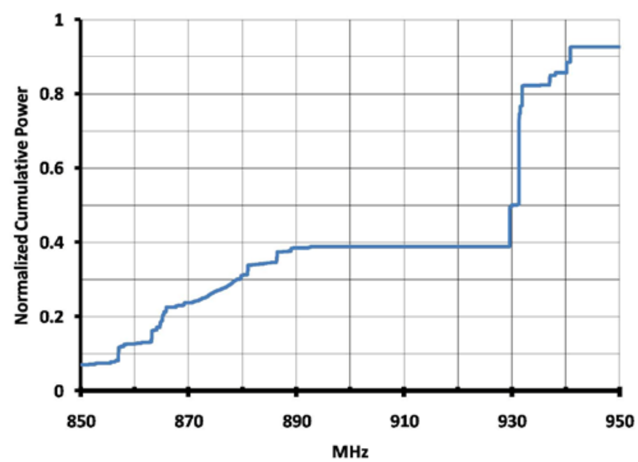

Figure 11: Normalized Cumulative Power

from this spectrum, the frequency concentration of the high power signals becomes more apparent.

Figure 11 shows the normalized cumulative power of the signal over the .8 GHz to 3 GHz band. Less 10% of the power is from the 800 MHz to 850 MHz range. Mostly cellular signals contribute about 30% of the power between 850 MHz and 890 MHz. Somewhat surprisingly, about 40% of the power in these 8-strongest waveforms comes from a narrow band between 928 MHz and 942 MHz.

6. A DESIGN STRATEGY

The results from the previous section suggest a compromise between frequency agility and wideband receiver dynamic range. If the vehicles are unlikely to use the 928 MHz to 942 MHz band, and it is practical and economical to filter the band out at the input of the wideband receiver, a significant reduction in the dynamic range requirement may be possible.

Table 1: Peak Value Reduction for the 8 Largest Waveforms

99th Percentile Voltage		99th Percentile Reduction (dB)
Without Filtering	With 930 MHz Notch Filter	
0.068	0.036	5.52
0.066	0.028	7.45
0.044	0.031	3.04
0.041	0.04	0.21
0.039	0.032	1.72
0.033	0.021	3.93
0.032	0.03	0.56
0.032	0.031	0.28

Wideband waveforms tend to have high peak-to-average values due to the presence of many carriers. Designing front-ends for the maximum value expected at the input is impractical. Rather, some degree of clipping is tolerated. The 930 MHz notch filter's performance was evaluated at 1% clipping by considering 99^{th} percentile magnitudes of the waveforms.

The efficacy of the 930 MHz notch filter can be seen in Table 1. A narrow band around 930 MHz was removed from the 8 largest waveforms. The table shows a reduction of about 6 dB in the 99^{th} percentile voltages for the largest of these signals.

7. SUMMARY

In this paper, a wideband (.8 GHz to 3 GHz) data collection mechanism is described. The wideband data collection concerns of thermal noise, the optimization of oscilloscope dynamic range, and overall spectral flatness are addressed. A spectral analysis of the collected waveforms suggested a possible design strategy that could reduce dynamic range requirements by 6 dB without introducing significant compromises in SDR front-end flexibility.

[1] F. H. Sanders, B. J. Ramsey, and V. S. Lawrence, "Broadband Spectrum Survey at San Diego, California," *NTIA Report 97-334*, Dec. 06

[2] *HP5250S Patterns.XLS*, Shakespeare Electronics, 2007

[3] *Users Manual, TDS6000B & TDS600C Series Digital Storage Oscilloscope, 2006*